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NUCLEAR WINTER: SMOKE GENERATION DEPOSITION AND REMOVAL

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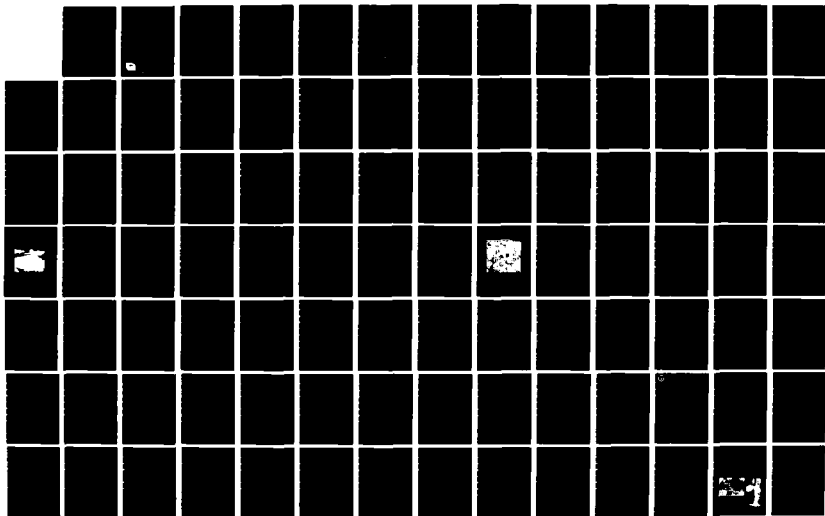
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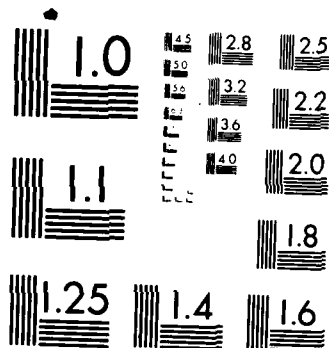
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IDA MEMORANDUM REPORT M-24

NUCLEAR WINTER:
SMOKE GENERATION, DEPOSITION, AND REMOVAL

Ernest Bauer

December 1984

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NUCLEAR WINTER: SMOKE GENERATION, DEPOSITION, AND REMOVAL

December 1984

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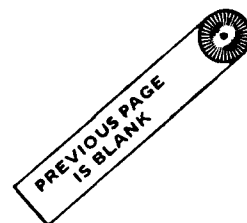
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Task T-4-237

PREFACE

This memorandum report was prepared under Task Order T-4-237 for the Defense Nuclear Agency during FY 1984 (see Appendix A). The effort applies to the (hypothetical) "Nuclear Winter" concept, and addresses the issues of atmospheric soot injection, emphasizing what one can learn from real atmospheric observations. Because of the short duration of this effort in a rapidly moving field, this document is presented as a progress report rather than as a definitive document.

ABSTRACT

The "Nuclear Winter" scenario predicts a major worldwide cooling arising from the large quantities of soot deposited in the atmosphere from fires ignited by the explosions in a large nuclear exchange. This document reviews the source function for smoke associated with urban and forest fires, addressing the smoke composition and predicted smoke cloud rise height. The interaction of the smoke cloud with the atmosphere is complex and depends on weather conditions. Results from past forest fires demonstrate what can actually happen to smoke clouds.



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This document has been reviewed by Frank Albini, Craig Chandler, and Freeman Hall.



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INTRODUCTION AND SUMMARY

The report, presented in part as an annotated briefing, was prepared under Task Order T-4-237 for the Defense Nuclear Agency during FY 1984 (Appendix A). The effort applies to the "Nuclear Winter" concept. That is, a large-scale nuclear exchange is predicted to start many extensive fires, both in cities and forests, which will generate large amounts of sooty smoke that will rise to high altitudes and stay in the atmosphere for long periods. Since the optical properties of soot are such that it absorbs visible radiation but transmits the earth's thermal (infrared) radiation, there is considerable concern that the effect of soot injection would be major worldwide surface cooling.

Figure S-1 shows the concept. As a result of molecular gases (mainly H_2O and CO_2) which transmit solar (visible) radiation but absorb earth (infrared) radiation, the temperature of the atmosphere decreases with altitude, so that the effective radiation temperature of the earth as a whole, $T_{rad} \sim 250\text{ K}$ (-23°C or -9°F), is significantly less than the surface temperature. The hypothesized injection of soot and dust which absorb or reflect sunlight while transmitting earthshine has been predicted by Turco et al. (1983) to produce an isothermal temperature profile in the troposphere (i.e., no change in temperature with altitude) so that the earth's surface temperature would fall to T_{rad} to maintain the overall energy balance.

No one has yet demonstrated that this "Nuclear Winter" scenario is physically impossible, and thus it is appropriate to investigate the problem.

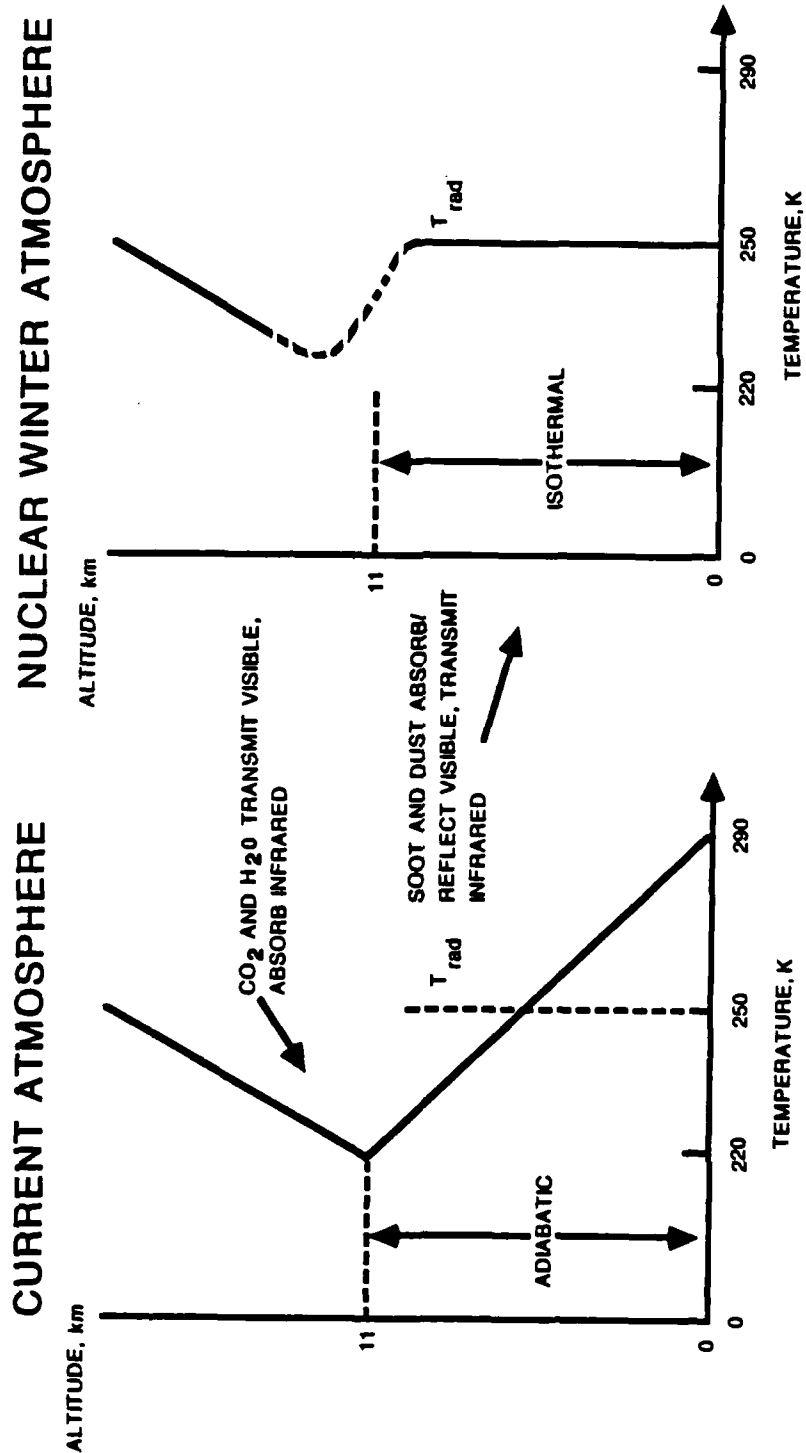


FIGURE S-1. The Nuclear Winter Concept.

In considering the problem, one must ask the following questions:

- How much smoke will be generated by a large-scale nuclear engagement?
- How long will this smoke remain in the atmosphere?

It must be recognized that because of the inherent variability of environmental (atmospheric and hydrologic) conditions, no unique answer can be expected for either of these questions even for a uniquely specified scenario for the nuclear engagement.

This document summarizes what we know and the major deficiencies in understanding about the generation, spreading, and removal of smoke resulting from large-scale urban and forest fires.

The topics addressed in Chapters 1 through 5 are the following:

1. Fuel loading (the mass of wood or other fuel per unit area contained in cities and in forests). It was concluded that forest fires can provide a partial simulation of large-scale urban fires.
2. Fire emission (the amount and composition of smoke per unit mass of fuel, with particular emphasis on the mass of soot per unit mass of fuel). A survey of fire emissions points out that soot is only a small fraction of the smoke produced by fires.
3. Fire model (the rate of energy release and smoke generation as a function of time, which gives a measure of the maximum injection altitude of the smoke).
4. The interaction of smoke plumes with the ambient atmosphere. How one gets from individual plumes to a hemispherical or global average presents a very complex problem. The plume expansion is a dynamic rather than a static problem, as can be seen by studying forest fires. The September 1950 Canadian forest fires which

gave rise to the "Blue Sun/Blue Moon" phenomenon--show that as the smoke plume moved in a generally easterly direction on the winds it spread horizontally, rose, fell, rose again to near the tropopause over Europe, and then, after 8 to 10 days, was observed no more. Accordingly, in discussion with DNA's Project Officer, Dr. Leon A. Wittwer, it was decided to devote the remaining effort to forest fires, and thus the final topic is:

5. What can be learned from forest fires? Chapter 5 reviews what can be learned from forest fires, such as the large fires that occurred in Western Canada in September 1950 which produced observable effects as far as the eastern U.S. and Western Europe. We have also included information on more recent fires in the Yukon, Borneo, and elsewhere.

Finally, Chapters 6 and 7 enlarge on the conclusions and recommendations that have been sketched here. It must be stressed that this document represents a progress and status report rather than a definitive treatment of the Nuclear Winter problem.

1. FUEL LOADING

FUEL LOADING DATA

- FOREST (Total Biomass)
 - 10 to 100 kg/m² = 2.05 to 20.5 lb/ft² = 100 to 1000 tonnes/ha
 - 4.45 kcal/g = 1.86 x 10⁷ J/kg = 8000 BTU/lb
- CITIES
 - Suburban
 - Two-story buildings, each floor 125 kg/m² (100 kg/m² structure + 25 kg/m² furnishings), 15% density, 37.5 kg/m² overall
 - Old City
 - Wood, high building density (40%), 200 kg/m²
 - New City
 - Ferro-concrete high-rise, 10% building density, wood and plastic, 40 kg/m² equivalent.

In terms of fuel loading, a forest fire is a tolerable partial simulation of a modern urban fire.

However, one must ask for fire loading, i.e., that fraction of the fuel loading which actually burns. In a typical forest fire most of what burns is duff, dead/down timber, and branches, bark, and leaves, leaving the commercial timber largely unburned. A major issue is the flammability, which varies widely from day to day, depending on how wet the ground and trees are.* F. Albin makes the following comments:

- "1. Flammability of wildland fuels on a hemispheric average basis will fluctuate widely with season. In addition, climatic zone variability is great over the North American Land mass--not quite so great over the eastern Soviet Union. But to make even an order-of-magnitude estimate, I would recommend using a 'typical day in the month of X' and averaging over X, rather than using monthly averages. This because on the typical day it will be raining--or recovering from rain--over a substantial fraction of any area even during that area's normal fire season.
- "2. The above procedure would still presumably apply a year or so after Armageddon. But wildland fuels over much of the Northern Hemisphere would be dead or dying from exposure to lingering radiation. Even the normally fire-free north central and northeastern US would become highly flammable in such a state. And the great expanse of forested Siberian USSR could probably be burned with a handful of matches in a few days. Thus I suggest that the level and distribution of plant mortality--especially conifer forests--may be a key question to be addressed.
- "3. For more details, see Chandler (1984)."

*Conventional firespread models (e.g., that of IITRI) postulate ignition at a thermal load of the order of 10 cal/cm^2 . Since the latent heat of evaporation of water or ice is in the range of 600 to 700 cal/g, 10 cal/cm^2 would evaporate 0.1 to 0.15 mm of water, or perhaps ten times as thick a layer of snow. Thus the presence of a relatively small amount of moisture will inhibit fire ignition in a forest.

In an urban fire, a large fraction of the combustible material may burn. Urban models typically postulate that ignition occurs inside a room by radiant energy transmitted through windows, so that ambient moisture would presumably not be important here.

Firestorms (such as occurred in Hamburg and probably also Dresden, Darmstadt, Heilbronn, and Hiroshima in World War II) appear to require three distinct sets of conditions to be satisfied:

1. A sufficiently large fuel loading--an older city with high building density and large amounts of wood, or possibly an inner city with high-rise buildings and flammable contents. (A modern spread-out suburban city probably cannot support a firestorm.)
2. A sufficiently large total area, $> 1 \text{ km}^2$, which is ignited simultaneously rather than sequentially.
3. Appropriate meteorological conditions which may depend on the particular location. Thus Ebert (1963), who has analyzed the meteorological conditions of the Hamburg firestorm, concludes that the actual weather was quite unusual, with a daily high temperature some 5 to 8°C above the normal maximum for the month (July).

I'll say very little about firestorms, but see Carrier et al., 1982.

FUEL LOADING - SOME DETAILS, 2

• PETROCHEMICALS/ASPHALT*

BLACKTOP ROADS IN A GERMAN CITY - 20 kg/m², 15% DENSITY

+ ADD 30% FOR ROOFING

+ ADD 100% FOR STORED FOSSIL FUEL

• ASSUME 25% BURNS, AS AGAINST 50% FOR WOOD

• ASSUME 12,000 BTU/lb, i.e. 50% MORE THAN WOOD

• WHOLE IS EQUIVALENT TO 1.2 lb/ft² @ 8000 BTU/lb

Crutzen and Galbally, unpublished, 1984

REPRESENTATIVE TRACTS IN DETROIT

ASSUME: 25 lb/ft²/floor IN HOMES (122 kg/m²)

10 lb/ft²/floor IN HIGH-RISE BUILDINGS (49 kg/m²)

TYPE	DESCRIPTION	HEIGHT, STORIES	DENSITY	FUEL LOADING lb/ft ² kg/m ²	FRACTION OF TRACTS
2	HOMES	1 (100%)	0.15	3.75 18.3	0.385
5	HOMES	2 (100%)	0.15	7.5 36.6	0.055
6/7	HOMES	2 (100%)	0.20	10 48.8	0.142
12/13	HOMES	1 (70%), 2 (30%)	0.15	4.9 24	0.272
15	HOMES	1 (70%), 2 (30%)	0.20	6.5 32	0.035
19	HOMES	2 (60%), 3 (40%)	0.20	12 58.5	0.016
24	APARTMENTS	3 (60%), 4 (20%), 5 (20%)	0.25	36 176	0.019
25	HIGH RISE (RESIDENTIAL)	14 (100%)	0.10	14 68	0.008
26	DOWNTOWN	6 (50%), 20 (30%), 30 (20%)	0.40	60 293	0.008
27	INDUSTRIAL	4 (60%), 6 (40%)	0.60	29 140	0.060

IF ALL TRACTS ARE EQUAL SIZE, TOTAL FUEL LOADING IS 8.07 lb/ft² or 39.4 kg/m²

MORE FUEL LOADING DATA
(All in lb/ft²)

Pacific Sierra Research
(Larson and Small, 1982)

	<u>W</u>	<u>M</u>	<u>E</u>
Central city (main business district with high-rise office and apartment buildings).	48.0	84.0	128.0
Inner belt (residential/industrial belt of intermediate height).	13.5	21.6	37.8
Outer belt (low, primarily residential).	3.6	6.4	10.0
W - lightly built up, represents a new, sprawling city (in U.S.)			
E - heavily built up, represents old, congested city (in U.S.)			
M - Intermediate building density			

Illinois Institute of Technology
Research Institute (IITRI)
(Longinow et al., 1982)

"Suburban city" 7.5

Forest (Total Biomass)

200 to 1000 tonne/ha = 4.1 to 20.5 lb/ft²

	Others
Turco et al. (1983)	3.8
Crutzen et al. (1984)	4.0

2. FIRE EMISSIONS

FIRE EMISSIONS

FOREST FIRE, WOOD:

- WOOD ISN'T DRY, CONTAINS 20 TO 30% H₂O
- 60 TO 80% COMPLETE COMBUSTION (TO CO₂, CO, H₂O)
- 1 KG WOOD GIVES:
 - 1 KG H₂O
 - 1.1 TO 1.5 KG CO₂
 - 100 TO 200 G SMOKE:

ACETYLENE AND OTHER HYDROCARBONS

"VOLATILE ORGANIC COMPOUNDS"

"BROWN TARRY GOOP"

SOOT, GRAPHITIC (C/H ~ 1), 10 TO 30 G

- 2 TO 4 G NO_x

URBAN FIRE:

- MATERIALS ARE:
 - WOOD
 - PLASTICS:
 - POLYETHYLENE
 - POLYURETHANE
 - POLYVINYL CHLORIDE
 - HYDROCARBONS:
 - TAR
 - OIL
 - BLACKTOP ETC.

Soot (submicron particles of graphitic material with a C/H ratio of 1/1 or so) represents perhaps 5 to 30 percent of smoke. Appendix B gives a model for soot particles. Note that actual soot particles are not spherical, but rather long strands. See Prospero et al. (1983) for a current review of atmospheric aerosols.

Smoke also includes a variety of molecules (such as hydrocarbons from methane and acetylene, also many ring compounds, aldehydes, etc.) and particles, many of which absorb selectively in the infrared, so that they could produce obscuration and "greenhouse effect." See, e.g., Weast (1981), p. F-205F, and Appendix C.

The various hydrocarbons and oxides of nitrogen interacting with sunlight produce ozone and other oxidants, typically in the 5 to 10 km altitude range, giving rise to atmospheric smog.

An urban fire produces smoke like that of a wood fire but also contains the decomposition products of various plastics.

FOREST FIRE EMISSIONS

<u>Product</u>	<u>Emission, g/kg fuel</u>	<u>Comments</u>
CO ₂	1000 to 1750	1460 for 100 percent combustion of "C ₆ H ₉ O ₄ "; actual efficiency, 60 to 80 percent.
H ₂ O	250 to 750	For 30 percent fuel moisture, 300 g from combustion of "C ₆ H ₉ O ₄ ."
CO	20 to 100	
NO _x	0.5 to 10	2 - EPA standards for landscape refuse. 4 - Bauer (1982)
HC	5 to 50	50 percent is CH ₄ , C ₂ H ₄ ; C ₂ H ₂ .
VOC	"Hundreds of volatile organic compounds"	
Particulates from flaming combustion	10 to 30	40 to 50 percent* organic carbon, 20 to 30 percent graphitic carbon
Particulates from smoldering combustion	to 100	60 percent organic carbon, 1 to 2 percent graphitic carbon

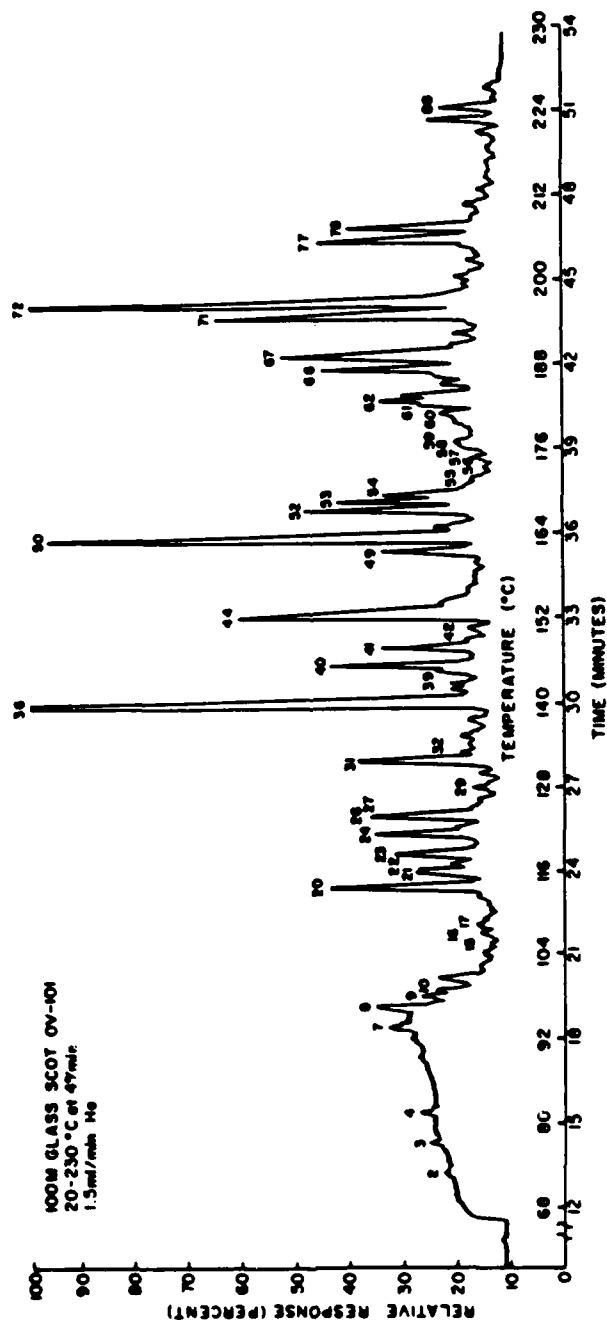
*Percent refers to total mass on the filter--a typical smoke is 50 to 60 percent C, 2 percent H, and the balance is O.
(See Patterson and McMahon, 1984.)

References: Chi et al. (1979), de Ris and Markstein (1984), McMahon (1983), Patterson and McMahon (1984), and Bauer (1982).

Winchester, Virginia Tire Fire,
December 1983

A small mountain of perhaps 9 million used tires, occupying 4-1/2 acres, some 5 miles west of Winchester, Virginia, just south of U.S. Highway 50, caught fire in November 1983. Probably the fire was deliberately set. This large fire presumably went on burning for a month or two. By 3 December, it had produced some 700,000 gallons of runoff, some of which was fairly good quality oil. The EPA helped control the fire, which was not easy to put out.

The fire reportedly sent up a dark plume, visible in three states, but on 3 December, under foggy conditions, I (Ernest Bauer) saw only smoldering white smoke; the forest was covered with a grey/white deposit. (Reference: Washington Post, 3 December 1983, "River Protected from Oil Oozing Out of Burning Mound of Tires" (see Appendix D).



PEAK	COMPOUND	PEAK	COMPOUND	PEAK	COMPOUND
2	isopentane	24A	acetaldehyde (tent.)	54	n-octane
2B	1-pentene	26	2,5-dimethylfuran	54A	2-isopropylfuran
2C	furan	26A	n-heptane	55	anisole
3	n-pentane	27	2,3-dimethyl-2-butene	56	2-methyl-5-isopropylfuran
3A	isoprene	29	2,3-dimethyl-2-pentene	57	cumene
3B	acetylene	31	2,4-dimethylhexane	58	n-decane
3C	isopropenol	32	toluene	59	camphene (tent.)
4A	cyclopentadiene	36	1-octene	60	n-propylbenzene
4B	diethylfuran	39	2,3-dimethylhexane	61	n-ethyltoluene
7	1-hexene	40	1,4-diene	62	n-decane
8A	methyl vinyl ketone	41	n-octene	64	benzofuran
9	2-methylfuran	42	2,3,5-trimethylfuran	67	limonene
10	n-hexane	44	terfenol	71	n-dimethylbenzene
15	2,4-hexadiene	49	ethyl benzene	72	limonene
16	1,5-hexadiene	50	n-nylene	77	n-α-dimethylstyrene
17	3-methylbutanal	50A	2-propenylfuran (tent.)	78	n-undecane
20	benzene	52	styrene	80	n-dodecane
21	cyclohexane	53	n-nylene		
22	4-methylpentene				
23	2A-dimethylbenzene				
24	1-trimethyl-2-dimethyl-cyclopentane				

Source: Forestry Source Management Guidebook

Chromatogram of organic vapors in loblolly pine smoke. Each peak represents a separate compound.

Polynuclear Aromatic Hydrocarbons from Burning Pine Needles by Fire Type (ng/g of fuel burned; dry-weight basis)¹

Polynuclear aromatic hydrocarbons	Beckung Fires			Heeding Fires		
	0.1 lb/ft ²	0.3 lb/ft ²	0.5 lb/ft ²	0.1 lb/ft ²	0.3 lb/ft ²	0.5 lb/ft ²
Anthracene/Phenanthrene	12,181	2,189	584	2,525	5,542	6,788
Methyl Anthracene	9,400	1,147	449	1,057	4,965	7,611
Fluoranthene	14,563	2,140	687	733	974	1,081
Pyrene	20,407	3,102	1,084	1,121	979	1,133
Methyl Pyrene/Fluoranthene	18,580	2,466	1,229	730	1,648	2,453
Benzo[a]phenanthrene	8,845	1,808	468	344	142	175
Chrysene/benzo[a]anthracene	28,724	5,228	2,033	581	543	636
Methylchrysene	17,753	1,891	877	282	1,287	1,589
Benzo[fluoranthene]	12,835	1,216	818	164	129	241
Benzo[a]pyrene	3,454	565	238	38	40	97
Benzo[b]pyrene	5,836	1,172	680	61	78	182
Perylene	2,128	198	134	33	24	46
Methylbenzopyrenes	6,582	963	384	65	198	665
Indeno[1,2,3-cd]pyrene	4,282	655	189	— ²	—	—
Benzo[ghi]perylene	6,181	1,009	419	—	—	—
Total	171,750	25,735	10,249	7,632	18,548	22,787
Total suspended particulate matter (TSP)	21	9	5	20	73	118
Benzene soluble organics	36	50	46	44	73	73

Polynuclear Aromatic Hydrocarbons from Burning Needles by Fire Phases (ng/g of fuel burned; dry-weight basis)¹

Polynuclear aromatic hydrocarbons	Flamming		Smoldering		Heeding Fires by Phases		Flamming		Smoldering	
	0.1 lb/ft ²		0.3 lb/ft ²		0.1 lb/ft ²		0.3 lb/ft ²		0.5 lb/ft ²	
Anthracene/Phenanthrene	1,612	7,049	865	9,046	2,351	8,791	1,909	11,447	1,331	1,331
Methyl Anthracene	838	3,872	687	8,183	622	1,331	888	1,391	1,331	1,331
Fluoranthene	448	2,317	344	1,616	622	1,331	888	1,391	1,331	1,331
Pyrene	750	3,078	342	1,484	888	1,391	1,331	1,331	1,331	1,331
Methyl Pyrene/Fluoranthene	465	2,363	494	2,801	1,036	3,396	1,036	3,396	1,036	3,396
Benzo[a]phenanthrene	228	387	77	188	179	173	179	173	179	173
Chrysene/benzo[a]anthracene	472	1,324	230	768	628	980	628	980	628	980
Methylchrysene	363	697	343	1,909	466	2,390	466	2,390	466	2,390
Benzo[fluoranthene]	178	189	89	174	80	347	80	347	80	347
Benzo[a]pyrene	33	100	17	85	36	140	36	140	36	140
Benzo[b]pyrene	86	133	46	102	82	303	82	303	82	303
Perylene	38	33	14	32	27	61	27	61	27	61
Methylbenzopyrenes	19	387	82	304	75	1,088	75	1,088	75	1,088
Indeno[1,2,3-cd]pyrene	—	—	—	—	—	—	—	—	—	—
Benzo[ghi]perylene	—	—	—	—	—	—	—	—	—	—
Total	5,897	21,779	3,456	26,324	8,389	31,519	8,389	31,519	8,389	31,519
Total suspended particulate matter (TSP)	13	55	11	165	31	222	31	222	31	222
Benzene soluble organics	38	48	54	76	68	76	68	76	68	76

¹Moisture content for all fires ranged between 18 to 27 percent
²None detected

Source: McMahon and Tsoukalas (1978)

Various organic molecules have absorption bands at selected regions in the IR (3 to 15 μm). See, e.g., Weast (1981), p. F-205f.

PHOTOCHEMISTRY

- SMOKE CONTAINS SOOT, HYDROCARBONS (HC), NO_x
- HC AND NO_x GENERATE OZONE IN TROPOSPHERE IN PRESENCE OF SUNLIGHT
- NO_x FROM FIREBALLS DESTROYS OZONE IN STRATOSPHERE
- SATURATION EFFECTS
- GREENHOUSE WARMING DUE TO HC

The hypothesized fires from a large-scale nuclear engagement will inject large quantities of soot, hydrocarbons, and other organic molecules and oxides of nitrogen (NO_x) into the troposphere while the nuclear fireballs will inject NO_x and dust into the stratosphere. An estimate of possible injections is given in Appendix C, Table C.1. In the presence of sunlight, hydrocarbons and NO_x generate ozone in the troposphere, while NO_x destroys ozone in the stratosphere. The total effect is complex and nonlinear, but may be significant.

The various IR-absorbing molecular gases will give rise to a greenhouse warming of probably less than 1°C (see Appendix C).

3. FIRE MODEL

COMBUSTION PRODUCTS AND ENTRAINED AIR PER KG FUEL (WOOD)

- AIR
 - ~ 10 KG AIR (+ FACTOR 2)
 - PERHAPS 100 TO 1000 KG AIR ENTRAINED DURING CLOUD RISE
(LESS FOR VERY LARGE FIRES)
- WATER
 - 1 KG FROM COMBUSTION
 - 1 TO 10 KG WATER MAY BE ENTRAINED IN CLOUD RISE
(LESS FOR VERY LARGE FIRES)
- SMOKE
 - 100 TO 200 G
- S00T
 - 10 TO 30 G

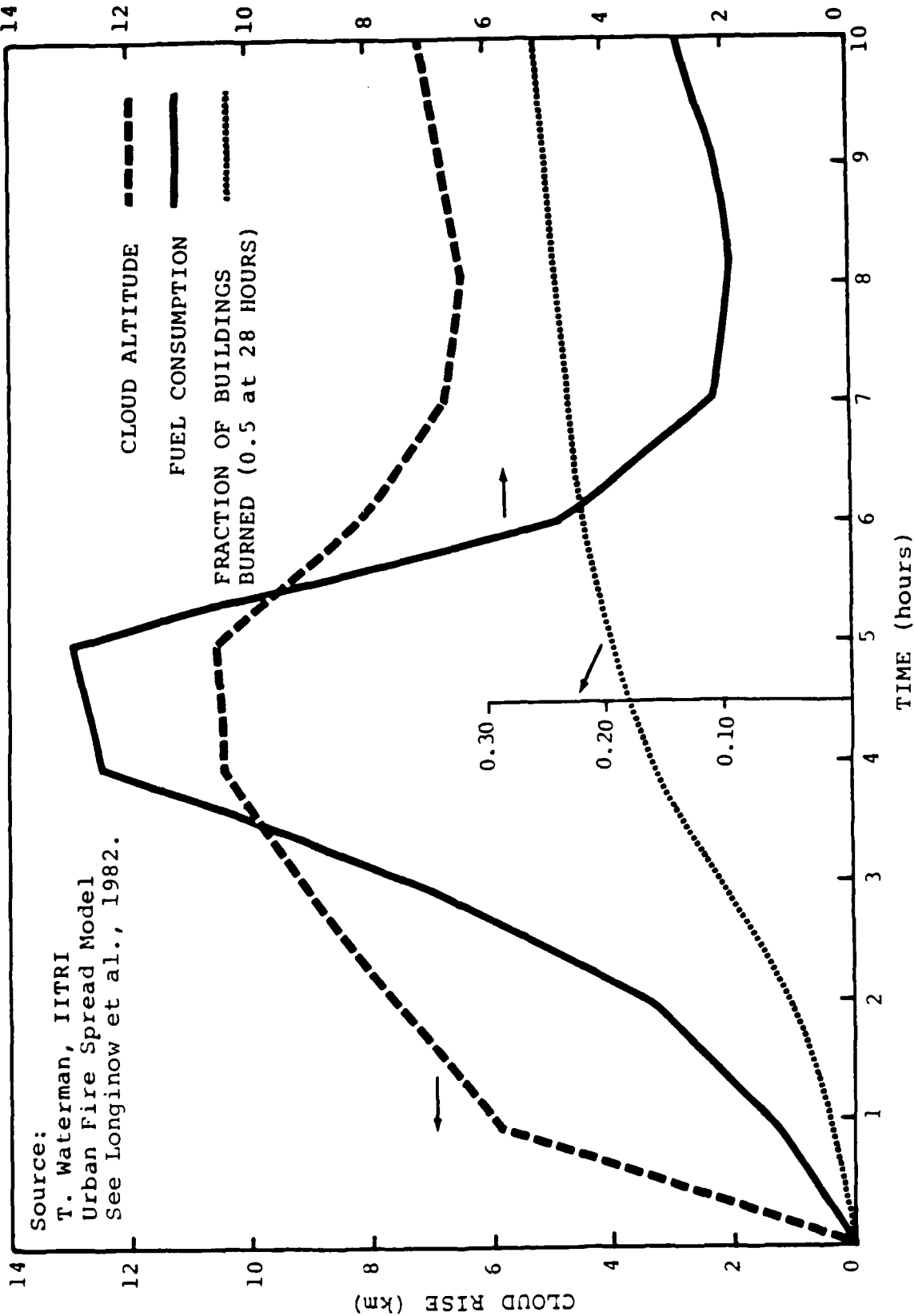
PLUME RISE

MAXIMUM ALTITUDE (MEIERS) = $46 Q^{1/4}$ (Q = POWER IN KW)
(MORTON, TAYLOR, TURNER, 1956)

- FORMULA APPLIES FOR
 - SMALL THERMALS
 - ATMOSPHERE WITH CONSTANT LAPSE RATE
 - STEADY SOURCE
- DOES NOT TREAT
 - LARGE SOURCE (RELATIVE TO SCALE HEIGHT)
 - ENTRAINMENT OF AIR/WATER
 - DETRAINMENT/DEPOSITION
- WE NEED DETAILED HYDRODYNAMIC ANALYSIS TO CONSIDER
 - WATER ENTRAINMENT/CONDENSATION AS ENERGY SOURCE
 - LARGE SOURCE EFFECTS
 - DETRAINMENT/DEPOSITION

THE BURNING OF "DETROIT"

Source:
T. Waterman, IITRI
Urban Fire Spread Model
See Longinow et al., 1982.



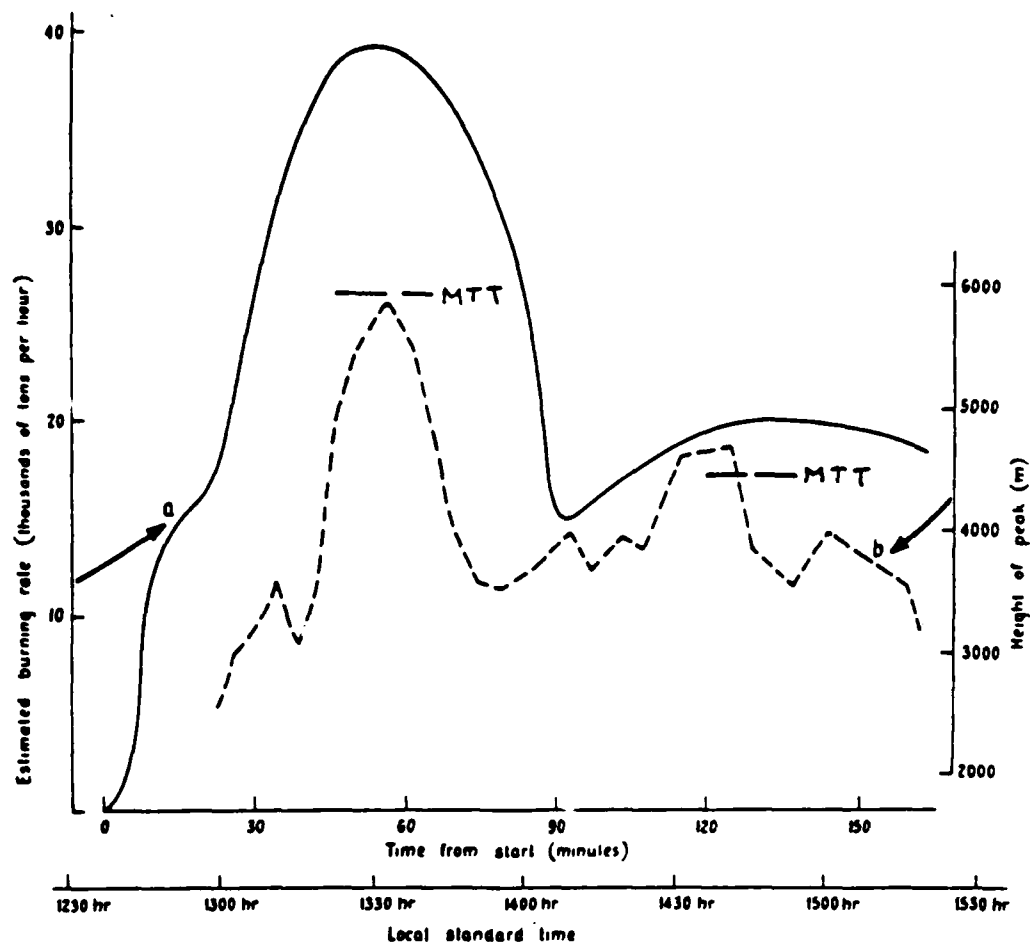
Urban fire spread models have been developed, largely under FEMA sponsorship (see Takata and Salzberg, 1968 and Longinow et al., 1982). These models predict four phases:

1. An incubation and exponential growth phase
2. A phase of maximum burning
3. A phase of steady but less intense burning
4. Finally, a phase of relatively low-intensity burning or smoldering.

Phases 1 and 2 each last 2 to 4 hours in a representative city, while phases 3 and 4 last somewhat longer (10 to 20+ hours). The duration and intensity of phase 4 is somewhat indeterminate since fire fighters (professional or ad hoc) may be able to put out the fire relatively easily at this stage.

The general characteristic of these four phases is also found in forest or bush fires. See the example of p. 3-7 of an Australian bush fire.

Note however that the fire initiation mechanisms for nuclear-induced urban and forest fires are different (see pp. 1-4, 1-5) so that ambient soil moisture, etc., will affect forest fires much more than urban fires, although for a suburban environment it will become important.



Estimated fuel burning-rates (a), and height of convection column (b), as a function of time.

DATA FROM AN INTENSE BUSH FIRE IN AUSTRALIA

(4000 HA, I.E., $(6.3)^2 \text{ km}^2$; SIZE OF (SHORT-LIVED) CONDENSATION CLOUD--A LITTLE MORE THAN 10% OF TOTAL FIRE AREA: 1 LB/FT²)

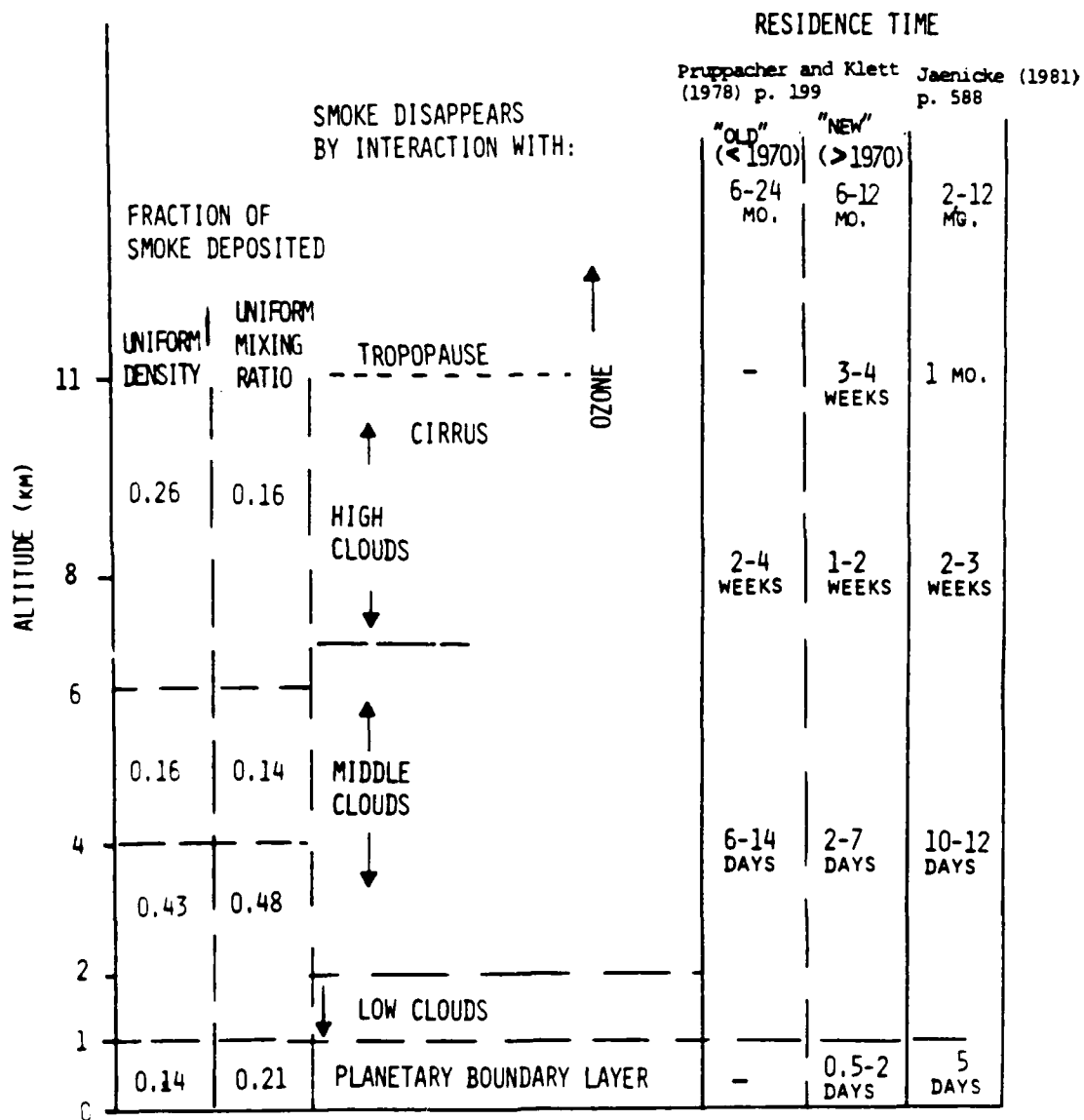
(SOURCE: R.J. TAYLOR ET AL., "CONVECTIVE ACTIVITY ABOVE A LARGE-SCALE BUSHFIRE," J. APPL. METEOROL., 12 1144 (1973))

(MTT: $H = 46 Q^{1/4}$; H IN M, Q IN KW)

SCHEMATIC OVERALL MODEL FOR BURNING

<u>PHASE</u>	<u>INITIAL</u>	<u>MAXIMUM COMBUSTION</u>	<u>SECONDARY</u>	<u>LOW/SMOLDERING</u>
DURATION (HRS)	(1-) 2	(-4)	12	24-48
FRACTION OF FUEL BURNED IN EACH PHASE	0.1	0.4	0.4	0.1
AEROSOL MASS AS FRACTION OF FUEL BURNED	2%	3%	3%	10%
FRACTION OF TOTAL AEROSOL	0.08	0.33	0.33	0.25
MAXIMUM PLUME ALTITUDE IN THIS PHASE (KM) (FROM MTT)	8.6	10.5	7.8	4/3.5

SMOKE DEPOSITION AND SCAVENGING
STATIC PICTURE--DO NOT USE



In a static or average picture, the altitude distribution at which the smoke is deposited is critical, because it determines the mean atmospheric residence time, which in the troposphere is largely due to rainout. In particular, that fraction of the smoke which is deposited relatively low (say, below 6 km) will tend to be scavenged rather fast by clouds and precipitation.

The residence time data describe precipitation scavenging in a coarse sense. The range of variability of residence time data reflects the geographical variation in precipitation as well as our overall level of ignorance. The fact that both sources agree in the tropopause region and differ by up to a factor of ten in the boundary layer probably indicates that there are now sufficient data on the boundary layer so that we recognize the variability; presumably, this is not so in the tropopause region.

This static or average picture is not generally applicable.

1. Large-scale motion of the fire plume is very complex, and depends strongly on actual, local (not average) weather and soil moisture conditions.
2. There will probably be some immediate local scavenging of soot in the form of fire-induced "black rain" (see, e.g., Molenkamp, 1979).
3. Any residual smoke cloud will absorb solar energy and thus will rise due to solar-induced buoyancy, a process for which arctic haze may provide a partial simulation (see Appendix E).
4. Indeed, this residual cloud will move as part of the circulation of the ambient atmosphere. Factors determining the interaction of the cloud with the atmosphere are discussed in Chapter 4. A good example of the large-scale and long-time motion is provided by the Western Canadian forest fires of September 1950, which are discussed in Chapter 5 in the general context of what one can learn from large-scale forest fires.

4. INTERACTION OF PLUME WITH ATMOSPHERE



THE TILLAMOOK FIRE IN ERUPTION, 1933. DURING THE MAIN BLOWUP, THE SMOKE COLUMNS REACHED THROUGH A LAYERED ATMOSPHERE TO HEIGHTS OF 37,000 TO 40,000 FEET.

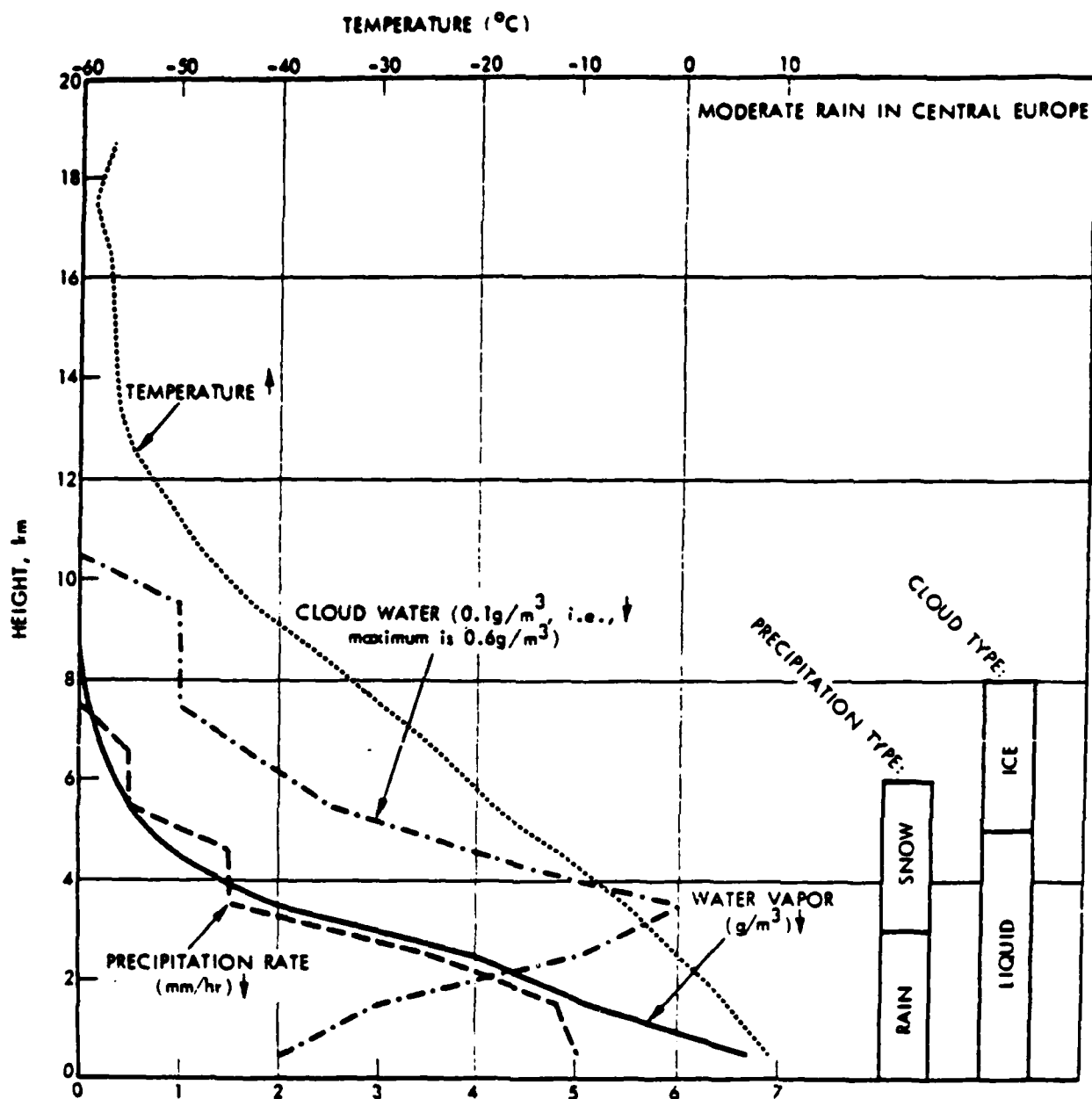
PLUME INTERACTION WITH AMBIENT METEOROLOGICAL CONDITIONS

- BLACK/BROWN CLOUDS TURN GREY/WHITE ABRUPTLY AT THE CONDENSATION LEVEL IN THE ATMOSPHERE
- SELF-INDUCED SCAVENGING PRODUCES SOME MEAN LOWERING OF INJECTED SMOKE
- OVERSEEDING DUE TO TOO MANY CONDENSATION NUCLEI REDUCES SCAVENGING
- INTERACTION WITH WATER CLOUDS:
 - CUMULONIMBUS
 - CUMULUS
 - STRATUS
- INTERACTION WITH OZONE
- ENTRAINMENT AND DETRAINMENT/DEPOSITION DURING CLOUD RISE
- LONG-TERM MOTION OF SMOKE CLOUD

LOCATION	FREQUENCY OF OCCURRENCE OF CLOUDS AT DIFFERENT ALTITUDES ¹				MEAN ANNUAL PRECIPITATION ² (MM)
	HIGH (> 7 km)	MIDDLE (2 to 7 km)	LOW (< 2 km)	TOTAL	
OTTAWA, CANADA	0.23	0.49	0.41	0.65	860
PUEBLO, COLORADO	0.21	0.25	0.26	0.44	360
BERLIN	0.29	0.54	0.50	0.44	580
MOSCOW	0.28	0.48	0.41	0.63	640
VLADIVOSTOK	0.17	0.30	0.56	0.51	610

¹3DNEPH DATA FROM MALICK AND ALLEN (1978, 1979)

²COJAY (1963)



5-27-75-22

Model Sounding for Moderate Rain in Central Europe
(Source: Woronicz, 1972, Table 15.)

TRANSITION FROM LOCAL INJECTION TO GLOBAL SCALE

- DISPERSION TIME TO HEMISPHERIC COVERAGE, 3 MONTHS (\pm FACTOR OF 2)
- DISPERSION TIME TO GLOBAL COVERAGE, 1 TO 2 YEARS (?)
- CHARACTERISTIC TIME FOR RAINOUT IN AMBIENT ATMOSPHERE:
 - BELOW 5 TO 6 KM: 1-2 WEEKS
 - ABOVE 5 TO 6 KM: 1-3 MONTHS
- LOSS RATE IN LOWER STRATOSPHERE:
 - TRANSPORT 6-12 MONTHS
 - OZONE REACTION ??
- SELF-INDUCED RAINOUT
 - 20-25% LOSS (LLNL)
- INITIAL SCAVENGING IN SPREADING FROM SOURCE TO HEMISPHERIC AVERAGE MAY BE LARGE
- NOTE THAT:
 - OVERSEEDING OF CLOUD MAY REDUCE SCAVENGING
 - THERMAL BUOYANCY MAY RAISE CLOUD ALTITUDE/LIFETIME TO TROPOPAUSE LEVEL
 - LARGE-SCALE METEOROLOGICAL EFFECTS MOVE CLOUD VERTICALLY (UP OR DOWN) AS WELL AS HORIZONTALLY

R. FRISTROM AND M. LINEVSKY

DESTRUCTION OF SOOT BY REACTION WITH OZONE AT HIGH ALTITUDES

- SOOT REACTS WITH FREE RADICALS - MOST
COMMON REACTIVE SPECIES IS OZONE
- $C(\text{SOLID}) + O_3 = CO + O_2$ - EXOERGIC - BUT COULD BE
CHEMICALLY LIMITED (E_{ACT})
- AT 10 KM, $N(O_3) \sim 10^{12} \text{ cm}^{-3}$, MIXING RATIO $\sim 10^{-7}$
(REACTION TIMES WILL BE LONGER AT LOWER ALTITUDE,
SHORTER AT HIGHER ALTITUDES)
- TOTAL AMOUNT OF ATMOSPHERIC OZONE MATCHES CRUTZEN ET AL.
MAXIMUM SOOT INJECTION
- REACTION KINETICS
RATE OF DESTRUCTION IS LIMITED BY: CHARACTERISTIC DISAPPEARANCE
TIME OF $C(s)$ OR O_3
- COLLISION: $E_{ACT} = \begin{cases} 0 & 2 \text{ MIN.} \\ 4 \text{ KCAL/MOLE} & 10 \text{ DAYS} \end{cases}$
- DIFFUSION OF OZONE TO PARTICLE SURFACE 2 MIN.
- TURBULENT ENTRAINMENT WHICH IS DIFFUSION-LIMITED
BELOW MINIMUM EDDY SCALE l_E -
 $l_E = 1 \text{ M}$ 10 MIN.
 $l_E = 10 \text{ M}$ 1/2 DAY

This will presumably be an important soot removal mechanism at altitudes above 6 to 8 km where there is rather little precipitation scavenging (see p. 4-6; precipitation scavenging is very slow for precipitation rates less than 0.1 mm/hr). The other principal soot removal mechanism at these altitudes would be transport by downward air flow, such as is associated with tropopause folding (see Danielsen, 1980 and Danielsen and Hipskind, 1980).

Experimental work is currently under way by R. Fristrom et al. at Applied Physics Laboratory to measure the rate of decomposition of soot by reaction with ozone. No results are available yet.

CLOUD PHYSICS CONSIDERATIONS

- CARBON BLACK AS CLOUD SEEDANT

- NRL EXPERIMENTS--VAN STRATEN ET AL. (1958)

CARBON BLACK ADDED TO FLORIDA CUMULUS REMOVES SOME CLOUDS

INJECTED NEXT TO CUMULUS, CARBON BLACK SOMETIMES LEADS TO CLOUD FORMATION

VERY COMPLEX

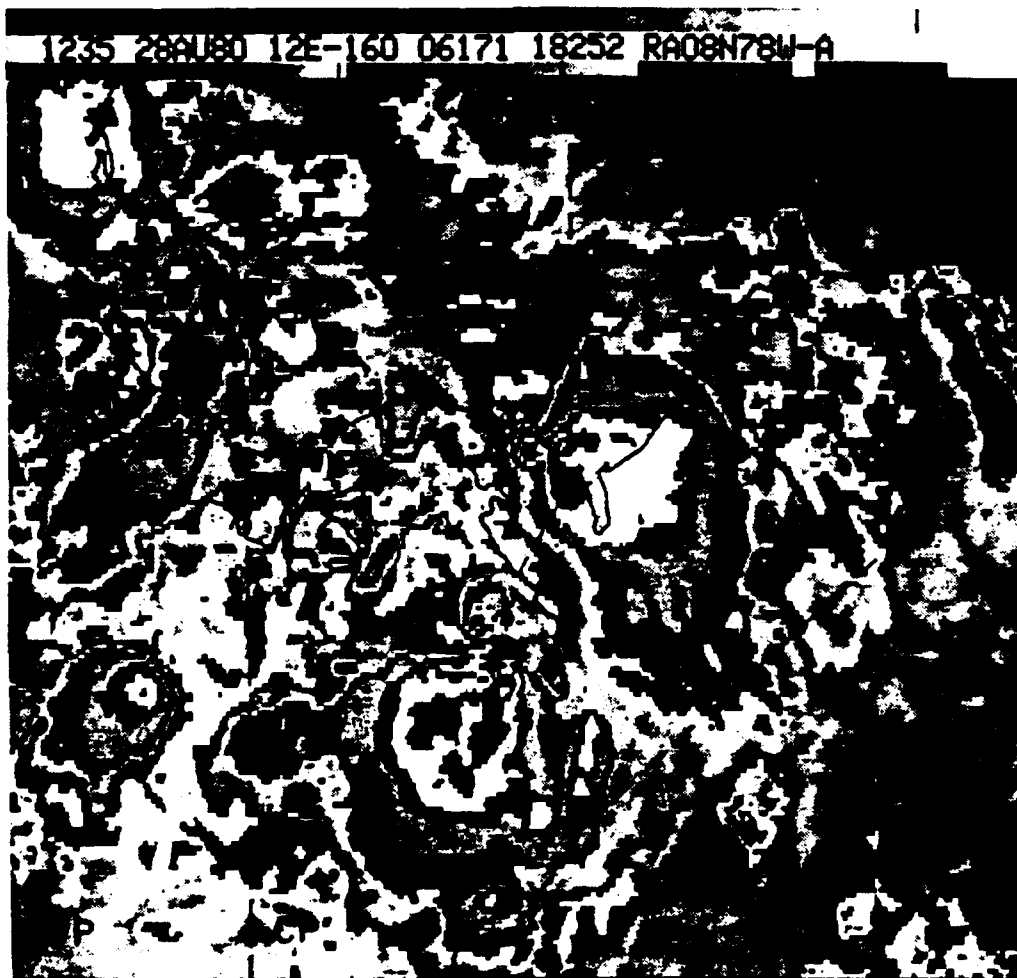
- DEPOSIT CARBON BLACK ON LOW CLOUDS FOR MESOSCALE WARMING

- CSU ANALYSIS--GRAY ET AL. (1976)

- CUMULONIMBUS INTERACTIONS

- SATELLITE OBSERVATIONS IN THE TROPICS DEMONSTRATE THAT SEPARATED CUMULO-NIMBUSES INTERACT/COALESCE ON SCALES ON THE ORDER OF 200 KM, 3 TO 5 HOUR TIME SCALE--DANIELSEN (1982)

- POSSIBLE INTERACTION OF NEIGHBORING PLUMES



200 km

Source: Danielsen (1982)

Enhanced infrared photo of clouds over Isthmus of Panama and northwestern South America. Cold anvils evident by transition from black to white ($T = -70^{\circ}\text{C}$), white to light grey ($T = -76^{\circ}\text{C}$) and to dark grey ($T = -82^{\circ}\text{C}$).

5. WHAT CAN ONE LEARN FROM FOREST FIRES?

SOME HISTORICAL EVENTS

- Plummer (1912) noted many periods of dark days in the U.S. and Canada, beginning with 1706, most of them caused, presumably, by forest fire smoke. Smoke from the great Minnesota forest fire of 13-17 October 1918 reached the Atlantic seaboard in surface air (Wexler, 1950).
- In 1915, an area of nearly 1.4×10^7 ha (50,000 mi², which exceeds the total forest area of France) of forest area in Western Siberia was damaged by fire (Antsyshkin, 1957). The smoke cloud over Siberia occupied an area equal to the whole of Western Europe, delaying crop maturation for...3 weeks (Artsybashev, 1974).
- In 1921,...the forests of the Mari Autonomous Soviet Republic continued burning throughout the summer. Over 35,000 people fought the fire for several days, but almost 3×10^5 ha (1000 mi²) of mature commercial wood area were destroyed (Artsybashev, 1974).
- During the last 10 days of September 1950, a smoke pall spread over portions of Canada, the Eastern U.S., and Western Europe. This...was unusual in the large area affected, and in the high concentration of smoke, which persisted in the Middle Atlantic States for... nearly a week (Wexler, 1950).

FOREST FIRE CONFLAGRATIONS IN SIBERIA(1915)

- Forest fires burned unimpeded from May to Sept.
- Covered 55000 square miles, equal to about 1/3 of western Europe.
- The fires were mostly crown fires and then burned the peat up to 6 feet deep.
- Smoke continuity lasted for 51 days.

Type 1 smoke--Continuous smoke, objects not perceptible over a distance of 350 feet (1,097,000 square miles).

Type 2 smoke--Nothing to be seen at a distance of 77 to 350 feet (833,000 square miles).

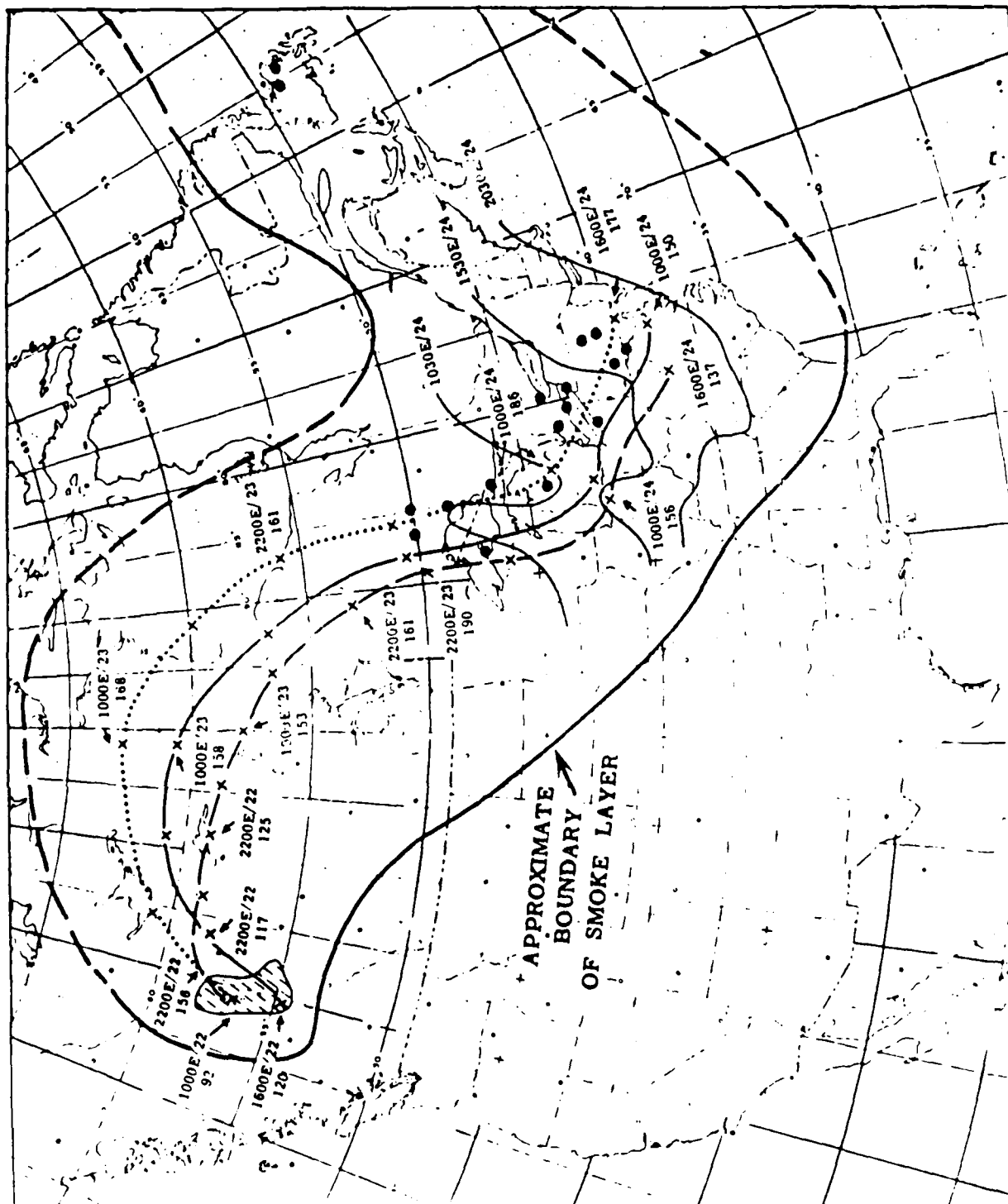
Type 3 smoke--Nothing to be seen at a distance of 14 to 77 feet (702,000 square miles).

- Visual range: 350 feet = $11,037 \mu\text{g m}^{-3}$
 77 feet = $46,800 \mu\text{g m}^{-3}$
 14 feet = $259,071 \mu\text{g m}^{-3}$
- Rainfall: on July 30 a very heavy smoke occurred in connection with a few drops of rain. Smoke became so dense that at 3:00 pm, day changed into night.
- Effects: Grass and hay were covered with soot with a smoky smell and bitter taste, "sickness among the cattle resulted from the use of this fodder."
- In July 1915, 85 percent of normal sunshine was received and in August 65 percent of normal.

Source: D.E. Ward (USFS), from Shostakovitch (1925)

CANADIAN FOREST FIRES, SEPTEMBER 1950

- WARM, DRY, AIR MASS (HIGH POTENTIAL TEMPERATURE ^o) OVER WESTERN CANADA IN SEPTEMBER 1950, STARTED ABOUT 100 FOREST FIRES.
- SMOKE PLUME OBSERVED OVER EASTERN U.S. AND OVER EUROPE:
 - PLUME SEEN, SOMETIMES REPORTED JUST AS CLOUD
 - BLUE SUN AND BLUE MOON REPORTED
 - ODOR OF BURNING PAPER REPORTED BY AIRCREWS
 - NO COOLING REPORTED
- CHRONOLOGY:
 - 22 SEPTEMBER, PLUME MOVES FROM B.C., ALBERTA
 - 24 SEPTEMBER, OBSERVED OVER EASTERN U.S. AT 10,000 TO 15,000 FT
 - 26 SEPTEMBER, REPORTED OVER U.K. AT 30,000 TO 38,000 FT
 - 27 SEPTEMBER, REPORTED OVER EUROPE (GROUND OBSERVATIONS)
 - 29-30 SEPTEMBER, REPORTED OVER GIBRALTAR, MALTA (GROUND OBSERVATIONS)
- SMOKE PLUME/CLOUD APPEARED TO FOLLOW ISENTROPES, NOT ISOBARS. HIGH ^o EVENTUALLY GOES TO TROPOPAUSE REGION. MATERIAL MAY HAVE GONE DOWN IN PASSAGE TO EASTERN U.S., THEN RISEN IN TRANSPORT TO EUROPE.
- AIR MASS TYPICALLY HAS 1 TO 2 WEEK LIFETIME, LITTLE GOES INTO THE STRATOSPHERE.



The figure (from Smith, 1950) shows trajectories of air parcels calculated on isentropic tracks for $\theta = 312$ K. Dashed hatching represents the fire area. Three-digit numbers by trajectory points are altitudes in hundreds of feet. Large dots near the Great Lakes mark stations reporting greatly diminished daylight on 21 September. Large dots in Newfoundland show the same on 25 September. The thin solid lines across the Great Lakes and the Eastern U.S. are isochrones at 5-hour intervals on 24 September, showing southeastward progress of the smoke layer.

Smoke plume height was 3 to 6 km over the U.S., 9 to 11 km over Europe. Generally, a plume rises due to solar heating; due to atmospheric motions, it rises in moving northward, sinks in moving southward.

Estimates of the total quantity of smoke generated are consistent with models within a factor of 3 to 10 (see Appendix F, item F.2).

AMBIENT METEOROLOGICAL CONDITIONS CAN BE CRITICAL

- FOREST FIRES ARE ASSOCIATED WITH WARM AIR MASSES - HIGH POTENTIAL TEMPERATURE, WANT TO MOVE ISENTROPICALLY TO TROPOPAUSE
- ENERGY DIFFERENCE BETWEEN "COLD" AND "WARM" AIR MASSES VERY LARGE (SEE APPENDIX G)
- SOLAR HEATING GIVES SIGNIFICANT BUOYANT RISE, $\sim \text{KM/DAY}$
- PRESUMABLY, NUCLEAR WAR WOULD OCCUR DURING AVERAGE WEATHER, NOT BIASED TO WARM, DRY AIR MASS AS ARE FOREST FIRES

CURRENT EVENTS

Yukon, July/August 1982

- 2×10^6 ha burned for 2 months.
- Plume followed same general track as in September 1950. One branch went to Britain, some dissipated over Cape Hatteras.

Borneo, 1982 - 1983

- 3.6×10^6 ha (August to October 1982, April to May 1983). See Appendix H.
- Multispectral data from NOAA polar orbiters being analyzed.

Australia, February 1983

- 0.3×10^6 ha (Voice and Gauntlett, 1984).

Siberia, July 1984

- Large smoke plume reported.

SOME CHARACTERISTICS

High-latitude Event

- Motion and scavenging representative of Nuclear Winter scenario.

Low-latitude Event

- Relatively high fuel loading.

TTAPS Base Case

- Fire, 150×10^6 ha, 30 kg/m^2 , 50% burned.

Multi-spectral Imagery on NOAA Satellites

- Visible -- shows smoke plume (not too thick optically)
- $0.9 \text{ } \mu\text{m}$ -- penetrates haze.
- $3.8 \text{ } \mu\text{m}$ -- goes to surface, sees hot spots.
- $11 \text{ } \mu\text{m}$ -- plume appears cold against earth background.

(Hope to learn plume height and/or IR absorption of molecular species in plume).

It is clear that forest fires occur only under a relatively limited set of meteorological conditions. In Siberia, Alaska, and Northern Canada there is a well-defined fire season, typically from June through August, and even then only when the ground and woods are very dry, which occurs frequently in some years, but very rarely in other years. However, when a forest fire burns it does simulate the general characteristics of urban fires, and probably provides the best available simulation. A particularly good simulation in terms of fire loading (but not meteorology) comes from land clearing in Brazil, and this will be investigated further.

FOREST FIRE AS PARTIAL SIMULATION FOR URBAN FIRE SOURCE

- DATA ARE (OR CAN BE MADE) AVAILABLE.
- FUEL/FIRE LOADINGS ARE COMPARABLE.
- NO "FIRESTORMS."
- SMOKE COMPOSITION: WOOD/PEAT VS. PLASTICS, ASPHALT, ETC.
- VERIFICATION OF PLUME RISE, DEPOSITION, AND DISPERSION MODELS.
- LARGE-SCALE MOTION UNDER SPECIFIED WEATHER CONDITIONS: WARM/DRY ONLY
- GENERALLY NO DIRECT INJECTION INTO THE STRATOSPHERE (BUT SEE P. 4-3).

6. GENERAL COMMENTS AND CONCLUSIONS

6. GENERAL COMMENTS AND CONCLUSIONS

This paper has addressed some specific aspects of the Nuclear Winter issue and conclusions are presented in Section 6.2. However, some general comments on the Nuclear Winter issue would seem to be in order at this point.

6.1 GENERAL COMMENTS

The obvious question is, "how real is the Nuclear Winter threat?" The following remarks are an attempt to answer this question.

- No one has yet demonstrated convincingly that the Nuclear Winter concept is physically impossible, or that the numerical estimates of Turco et al. (1983) are wildly unreasonable, although estimates of the amount of cooling that would occur have tended to decrease somewhat, from 50°C to 20°C, as effects of the oceans are introduced.
- Teller (1984) suggests that the effects of climate change associated with Nuclear Winter will eventually be shown to be small compared with the direct physical damage resulting from a large-scale nuclear exchange.
- Whether and to what extent massive urban fires--as postulated in the Nuclear Winter Scenario--occur will depend on the scenario, and to some extent on environmental conditions (precipitation, snow cover, etc.). Presumably, if there are no nuclear attacks on cities, there will be no large urban fires.

- If there are nuclear attacks on cities, how likely is it that there will be large urban fires? We know, for example, that most forest fires occur near the end of a long, dry summer season. Current firespread models do not take into account any seasonal weather variations.* The effect of seasonal variations on firespread and plume rise is probably "not great," but should be better defined.
- If massive urban fires occur, their effects can range from relatively little to enormous. The 1915 Siberian forest fires burned some 15 million hectares (45 million acres) and reportedly delayed crop maturation for up to three weeks, but produced no noticeable global cooling.
- The reliability of the predictions is poor because the global climate models omit many factors which could be important. Probably the most significant uncertainty is the duration of the effect. The models have limited ocean-atmosphere interaction, which is critical in predicting long-term effects because of the very large heat capacity of the oceans. The models predict a fundamental change in the atmosphere, leading to much enhanced stability and thus less convection, precipitation, and scavenging than in today's atmosphere. Clearly, if the soot is not scavenged rapidly, the surface cooling could last much longer, giving a much more severe effect.

*Conventional firespread models (e.g., that of IITRI) postulate ignition at a thermal load of the order of 10 cal/cm^2 . Since the latent heat of evaporation of water or ice is in the range of 600 to 700 cal/g. 10 cal/cm^2 would evaporate 0.1 to 0.15 mm of water, or perhaps ten times as thick a layer of snow. Thus the presence of a relatively small amount of moisture will inhibit fire ignition in a forest. Urban models typically postulate ignition as occurring inside a room by radiant energy transmitted through windows, so that ambient moisture would presumably not be important here. In any case, it is clear that once a fire is well under way the effect of standing water or rain is probably negligible.

6.2 CONCLUSIONS

6.2.1 Fuel and Fire Loading

The fuel loading (mass of fuel per unit area) of forests and typical, modern spread out cities with suburbs are roughly comparable, but older, high-density cities constructed of wood rather than steel, brick, or concrete have significantly higher fuel loadings, giving rise to the possibility of "fire storms."

The issue of fuel loading vs fire loading (mass of fuel burned per unit area) is important. In a city, the fire loading may approach the fuel loading (although the effect of blast might be to reduce significantly the fraction of fuel burned), but in the average, not-very-intense forest fire it is mainly the leaves, needles, branches, and dead material on the ground that burns, leaving the tree trunks, which make up the major part of the fuel loading, largely unburned. This does not apply to the case of fires used for land clearing for commercial agriculture or stock raising. However, following an initial major forest fire, there are often periodic reburns over a period of years in which the material killed but not burned by the initial fire has dried and so become unusually flammable.

6.2.2 Fire Emissions

Smoke is an exceedingly complex mixture of particles and gases.* In particular there are many infrared active molecules present in smoke (in small concentration), which will lead to a "greenhouse" warming. The rough estimates presented in Appendix C suggest a warming of the order of 1°C, far less than the predicted Nuclear Winter Cooling.

The hydrocarbons and other, more reactive molecules emitted will undergo photochemical reaction in the presence of sunlight,

*"As of 1968, over 1200 chemical compounds have been identified in tobacco smoke. To date, over 200 compounds have been identified in wood smoke." (Quoted from Southern Forestry Smoke Management Guidebook, 1976, p. 11.)

possibly leading to a reduction in OH radicals and to ozone production through "smog" reactions. Indeed, these various effects may prove to be more significant on a long-term basis than the atmospheric injection of soot.

J.V. Smith (Geophysical Sciences, University of Chicago) pointed out on 5 September 1984 that there are large coal deposits in North Dakota, and raised the possibility that warheads detonated on or below the surface to destroy hardened Minuteman missiles could raise large quantities of coal dust high into the atmosphere. The mass of material lofted by a near-surface burst is of the order of 0.3 million tons per Mt. If 10 percent of this mass goes into the stratosphere, and if 10 percent of the total mass is coal dust, the detonation of 100 Mt of nuclear weapons will send some 3 million tons of coal dust into the stratosphere. This may be compared with the 11 million tons of soot sent into the stratosphere in the scenario "base case" in Turco et al. (1983).

6.2.3 Fire Models

There appears to be no good feeling about how reliable the urban firespread models are, at least with regard to how the rate of energy release depends on multiburst/blast effects and on ambient weather. Further, plume rise is strongly coupled to the rate of energy release, and the entrainment and detrainment of water vapor and the deposition of smoke or soot are not well understood.

6.2.4 Interaction of Plume and Atmosphere

Interaction of plumes with the atmosphere is a very complex, important, but barely studied problem. It is important because during the 1 to 3 week period in which the plumes from individual fires presumably merge and spread into a relatively uniform smoke pall there is the possibility of a number of different processes leading to rainout and other disappearance mechanisms. What goes on in this time period clearly depends very much on ambient weather.

Different plumes may interact, as do thunderclouds, leading possibly to enhanced cloud rise or to enhanced or reduced precipitation scavenging. In this context, the NASA stratosphere/troposphere interaction experiment (page 4-10; Danielsen, 1982; and Margozzi, 1983) may provide some useful information.

The possibility that soot and organic molecules may be destroyed by ozone and other ambient atmospheric oxidants is a very important one, especially at higher altitudes (above 5 to 6 km) where little precipitation scavenging occurs, and here the experiments of Fristrom et al., (1984) may be extremely significant.

One possible partial simulation may be provided by Arctic Haze (see Schnell et al., 1984 and Appendix E).

6.2.5 Forest Fires

It is clear that the long-range transport of a smoke plume is very important in determining the effect of the emitted smoke on local and regional insolation and weather, as well as, ultimately, on global climate. Here, forest fires provide a large and, as yet, largely unexploited data base, both actual and potential, which demonstrates how the smoke is dispersed. The best single source of data concerns by the Canadian forest fires of September 1950, but there are other data concerning fires in the Yukon (July 1982), Borneo (1982-83), Brazil, and possibly Siberia, that can be exploited.

A specific question deals with the duration of smoke effects. The plume of the Canadian forest fires which burned 1.5×10^6 ha was observed for 8 to 10 days, but no cooling was reported. The 1915 Siberian fires (15×10^6 ha) burned for 5 months and were reported (Artsybashev, 1974) to have delayed crop maturation for as much as 3 weeks.* By contrast, the

*This statement probably cannot be verified because cause and effect in climate variability cannot easily be ascribed since there are many contributing factors. Further, Professor H.E. Landsberg, University of Maryland, (private communication, 5 September 1984) points out that after mid-1914 Russian temperature records are not available, so that it is doubtful whether one can establish unequivocally that a regional cooling occurred or that, if it did, it was due to the forest fires.

standard Nuclear Winter scenario (Turco et al., 1983) corresponds to 150×10^6 ha burning, and climatic cooling on the order of months to several years is predicted.

7. GENERAL COMMENTS AND RECOMMENDATIONS

7. GENERAL COMMENTS AND RECOMMENDATIONS

As in Chapter 6, Conclusions, specific recommendations on the five general issues addressed in this work are outlined in Sections 7.2.1 through 7.2.5, but general recommendations on the overall Nuclear Winter issue are given first, in Section 7.1.

7.1 GENERAL RECOMMENDATIONS

Since one cannot discount the possibility of Nuclear Winter occurring, it is appropriate to investigate it. Based on the general conclusions of Chapter 6, the following general recommendations are offered.

- One key issue can be seen from Fig. 1: how can one get from the present atmosphere with an adiabatic troposphere to the postulated adiabatic state? To determine this one must examine how the smoke plumes from the individual fires merge and spread around the globe.
- Work should be done on scenarios to identify under what conditions, and to what extent, large-scale fires might occur.
- The dependence of fires on ambient weather and hydrological (soil, moisture, snow, etc.) conditions should be investigated, treating all aspects from ignition probability to plume rise and deposition.
- It must be established whether the predictions of enhanced atmospheric stability are robust, and how this changes scavenging rates and thus soot life time.
- Climate models need improvement, both insofar as additional physical processes are included and also

as predictions are verified by comparison with actual events such as urban and forest fires. Specific processes that should be considered include the following:

- Ocean/atmosphere interactions (since long-term climatic changes are largely mediated by the very great heat capacity of the oceans)
- Water/ice cloud effects on the radiative balance
- Surface snow/ice albedo feedback (Robock, 1984)
- Diurnal variation of insolation
- Appropriate ranges of scenarios and initial conditions

7.2 RECOMMENDATIONS

7.2.1 Fuel and Fire Loadings

The current methodology for determining fuel loadings is reasonably adequate, but fire loadings, which give the fraction of the fuel that is burned, are not so well established. More effort here may be appropriate, particularly in determining the effects of ambient environmental conditions (temperature, snow cover, etc.) and of blast damage on urban fire loadings. As a consequence of this, it may be appropriate to indicate in what fraction of possible scenarios one might expect large fires to occur.

7.2.2 Fire Emissions

Estimates of soot production are probably adequate within the range of plausible numerical values. However, it is appropriate to ask how rapidly the properties of soot particles change from being hydrophobic, since this will affect the rate of scavenging.

More detailed analysis of chemical species emitted by fires seems desirable in order to establish their potential long-range effect on atmospheric photochemistry and also their greenhouse effect, to improve on the crude model of Appendix B.

7.2.3 Fire Model

Issues here include the verification of firespread and plume rise models, including the effects of ambient weather and of blast damage on burning rate and air/water entrainment and smoke detrainment/deposition in the atmosphere. For the plume rise/deposition, cumulus convection models (e.g., Cotton, 1984) should be developed and applied. One question to be answered is: how much of the moisture and pollutants raised into the stratosphere by such a cloud are deposited in the stratosphere rather than transported down again.

7.2.4 Plume/Atmosphere Interaction

As pointed out in Section 7.1, it is absolutely crucial to determine how one gets from a normal adiabatic atmosphere to the isothermal one of Fig. S-1 (p. S-2). In this context it is essential to determine how the plumes from individual fires rise, merge with one another, interact with ambient weather systems, are scavenged, rise due to solar-induced buoyancy relative to their local isentropic trajectories, and eventually spread around the globe.

Some key questions include the following:

- How much self-induced scavenging will there be, giving rise to "black rain"?
- How fast is smoke destroyed by chemical reaction, presumably principally by the soot/ozone reaction? The experimental work of R. Fristrom et al., Applied Physics Laboratory (see p. 4-8f) should be supported. The problem is not a simple one, and a relatively broad but guided range of experimental studies could be extremely useful.
- How fast is smoke transported down from the tropopause region by convection, tropopause folding, etc., into the middle troposphere where it will presumably be scavenged by clouds and rain?

- What can be learned from arctic haze studies (see Schnell, 1984)? Appendix E lists a number of questions to be addressed, such as plume rise due to buoyancy, aspects of the soot-ozone reaction, and precipitation scavenging. However, further examination of these issues is appropriate.
- What are the effects of ambient weather conditions on long-range transport?
- How important are firestorms, as against other mass fires?
- What is the possible interaction between neighboring clouds, such as the effect studied for cumulonimbus by Danielsen (1982)?
- What are smog effects of nitrogen where soot and sulfur rather than oxides are primary pollutants (such as was formerly the case in Pittsburgh)?

7.2.5 Forest Fires

Small fires (prescribed burns) may be of use for studying emissions and plume rise under different conditions, but there is probably sufficient information from U.S. Forest Service experience (see, e.g., Southern Forestry Smoke Management Guide-Book (1976), Chandler (1984)). The experience from events such as the November 1983 Winchester, Virginia tire fire (see Appendix D), which has largely been recorded on video tape by NOAA (Nappo, 1984) is probably not very useful, but should not be dismissed without further thought.

Large forest fires such as those in the Yukon, Brazil, Borneo, and Siberia provide very useful information since they are large-scale phenomena whose plumes can be sensed remotely using the multi-spectral imagery provided by weather satellites, and thus long-range transport can be studied. However, there are several problems, namely:

- Mid/high latitude fires occur under weather conditions which are relevant to the scenarios for a nuclear exchange.

Forest fires at any latitude do not occur at random, but under very specific sets of weather conditions, that is, when a mass of warm, dry air is stationary over a given surface region for some weeks, producing conditions conducive to fire. The air mass has high thermal energy, which may simulate the heat of combustion of a burning city.

Tropical forest fires may not provide a very good simulation. Some of the most interesting situations are associated with land clearing for commercial agriculture. The scale (including fire loading) of some of these operations is large, but the ambient meteorology is quite different from mid/high latitude conditions. In particular, the 1982-83 Borneo fires extended over a very large area but had a low fire loading and consequently low initial plume rise height. However, any subsequent plume rise would be of great interest (see Appendix H).

BIBLIOGRAPHY

BIBLIOGRAPHY

- Albini, F., "The Spread of Fires in Wildland Fuels," U.S. Forest Service presentation at the Large-Scale Phenomenology Meeting, National Bureau of Standards, September 1984.
- Antsyshkin, S.P., "Forest Fire Protection," Goslesbumizdat, Moscow-Leningrad, (in Russian), p. 185, 1952.
- Artsybashev, E.S., "Forest Fires and Their Control," Lesnaya Promyshlennost' Moscow, (in Russian; translated for USDA and NSF by Amerind Publishing, New Delhi at TT 77-52050, p. 1, 1974.
- Bauer, E., "The Growth and Disappearance of Tracer Clouds in the Atmosphere," Institute for Defense Analyses, Note N-890, June 1983.
- Bauer, E., "Natural and Anthropogenic Sources of Oxides of Nitrogen (NO_x) for the Troposphere," FAA Report No. FAA-EE-82-7, January 1982.
- Bull, G.A., "Blue Sun and Moon," Meteorology, 80, 1, January 1951.
- Carrier, C.F., F.E. Fendell, and P.S. Feldman, "Firestorms," TRW, DANA-TR-81-102 (ADA-131147), April 1982.
- Chi, C.T. et al., "Source Assessment: Prescribed Burning, State of the Art," EPA Report No. EPA600/2-79-019h, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, November 1979.
- Church, C.R., J.T. Snow, and J. Dessens, "Intense Atmospheric Vortices Associated with a 1000 MW Fire," Bull. Am. Meteor. Soc., 61, 682, 1980.
- Conway, H.M., Ed., The Weather Handbook, Conway Publications, Atlanta, Georgia, 1963.
- Cotton, W.R., "A Simulation of Cumulonimbus Response to an Urban Firestorm -- Implications to a Nuclear Winter," Colorado State University presentation at Large-Scale Fire Phenomenology Meeting, National Bureau of Standards, 1984.

- Crutzen, P.J., I.E. Galbally, and C. Bruehl, "Atmospheric Effects from Post-Nuclear Fires," submitted to Climatic Change, 1984.
- Culkowski, W.M. et al., "A Photographic Study of a Massive Tire Fire," Atmos. Envir., 18, 893, 1984.
- Danielsen, E., "Statistics of Cold Cumulus Anvils Based on Enhanced IR Photographs," Geophys. Res. Lett., 9, 601, 1982.
- Danielsen, E.F., "Stratospheric Source for Unexpectedly Large Values of Ozone Measured Over the Pacific Ocean During Gametag, August 1977," J. Geophys. Res., 85, 401, 1980.
- Danielsen, E.F. and R.S. Hipskind, "Stratospheric-Tropospheric Exchange at Polar Latitudes in Summer," J. Geophys. Res., 85, (C1), 393, 1980.
- de Ris, J. and G.H. Markstein, "Estimated Particulate Emissions from Large Urban and Forest Fires," Note, 1984.
- Doherty, G.M., R.E. Newell, and E. Danielsen, "Radiative Heating Rates Near the Stratospheric Fountain," J. Geophys. Res., 89, (D1), 1380, 1984.
- Ebert, C.H.V., "The Meteorological Factor in the Hamburg Firestorm," Weatherwise, 16, 70, 1973.
- Elsley, E.M., "Alberta Forest-Fire Smoke--24 September 1950," Weather, 6, 22, January 1951.
- Fristrom, R., M. Linevsky, and D. Silver, "Atmospheric Ozone as a Chemical Scavenger of Soot," Applied Physics Laboratory Presentation at Large-Scale Phenomenology Meeting, National Bureau of Standards, 1984.
- Golike, R.C. et al., "Vibrational Intensities, VI. Ethylene and Its Deuterioisotopes," J. Chem. Phys., 25, 1266, 1956.
- Gray, W.M. et al., "Weather Modification by Carbon Dust Absorption of Solar Energy," J. Appl. Meteorol., 15, 355, 1976.
- Greenberg, J.P. et al., "Hydrocarbon and Carbon Monoxide Emissions from Biomass Burning in Brazil," J. Geophys. Res., 89, (D1), 1380, 1984.
- Jaenicke, R., "Atmospheric Aerosols and Global Climate," in Climatic Variations and Variability: Facts and Theories, A. Berger, Ed., D. Reidel, p. 577ff, 1981.

- Larson, D.A. and R.D. Small, "Analysis of the Large Urban Fire Environment, Part I, Theory," Pacific Sierra Report 1210, prepared for Federal Emergency Management Agency, July 1982.
- Longinow, A., T.E. Waterman, A.N. Takata, "Assessment of Combined Effects of Blast and Fire on Personnel Survivability, Illinois Institute of Technical Research Institute, prepared for Federal Emergency Management Agency, June 1982.
- Margozzi, A.P., Ed., "The 1980 Stratospheric-Tropospheric Exchange Experiment," NASA TM-84297, Ames Research Center, 1983.
- McMahon, C.K., "Characteristics of Forest Fuels, Fires and Emissions, "Paper No. 83-45.1, to be presented at the 76th Annual Meeting of the Air Pollution Control Association, Atlanta, Georgia, June 1983.
- McMahon, C.K. and S.N. Tsoukalas, "Polynuclear Aromatic Hydrocarbons in Forest Fire Smoke," in Carcinogens, Vol. 3, Polynuclear Aromatic Hydrocarbons, P.W. Jones and R.I. Friedenthal, Eds., pp. 61-73, Raven Press, N.Y., 1978.
- Morton, B.R., G.I. Taylor, and J.S. Turner, "Turbulent Gravitational Convection from Maintained and Instantaneous Sources," Proc. R. Soc. Lond., A234, 1, 1956.
- Palmer, T.Y., "Large Fire Winds, Gases, and Smoke," Atmos. Envir., 15, 2079, 1981.
- Patterson, E.M. and C. K. McMahon, "Absorption Characteristics of Forest Fire Particulate Matter," submitted to Atmospheric Environment, 1984.
- Penndorf, R., "On the Phenomenon of the Colored Sun, Especially the 'Blue' Sun of September 1950," Air Force Cambridge Research Center Technical Report 53-7, April 1953.
- Penner, J.E., "Tropospheric Response to a Nuclear Exchange," LLNL preprint UCRL-89956, October 1983.
- Plummer, F.G., "Forest Fires, USDA Forest Service Bulletin No. 117, U.S. Government Printing Office, 1912.
- Prospero, J.M. et al., "The Atmospheric Aerosol System: An Overview, Review of Geophysics, 21, 1607, 1983.
- Pruppacher, H.R. and J.K. Klett, Microphysics of Clouds and Precipitation, D. Reidel, 1978.

- Pyne, S.J., Fire in America, Princeton U.P., 1982.
- Rasmusson, E.M. and J.M. Hall, "The Major Pacific Warm Episode of 1982/83, WMO Bulletin, 32, #4, 301, 1983.
- Robock, A., "Snow and Ice Feedbacks Prolong Effects of Nuclear Winter," Nature, 310, 667, 1984.
- Rothman, L.S., "AFGL Atmospheric Absorption Line Parameters Compilation: 1980 Version," Appl. Opt., 20, 791, 1981.
- Rothman, L.S. et al., "AFGL Atmospheric Absorption Line Parameters Compilation: 1982 Edition," Appl. Opt., 22, 1983.
- Schnell, R.C., Ed., "Arctic Haze; the AGASP Program," Geophys. Res. Lett., 11, No. 5, 359-472, 1984.
- Shettle, E.P. and R.W. Fenn, "Models for the Aerosols of the Lower Atmosphere and the Effects of Humidity Variations on Their Optical Properties," AFGL-TR-79-0214, September 1979.
- Shostakovitch, V.B., "Forest Conflagrations in Siberia, with Special Reference to the Fires of 1915," J. Forestry, 23, 365, 1925.
- Smith, C.D., Jr., "The Widespread Smoke Layer from Canadian Forest Fires During Late September, 1950," Mon. Wea. Rev., 77-78, 180, September 1950.
- Smith, Philip, "River Protected from Oil Oozing Out of Burning Mound of Tires, Washington Post, p. B1, December 3, 1983.
- Takata, A.N. and F. Salzberg, "Development and Application of a Complete Fire-Spread Model, Volumes I through IV," Illinois Institute of Technical Research Institute, prepared for Office of Civil Defense, Report NRDL-TRC-68-36, AD Nos. 684874, 849732, 849733, and 849734, June 1968.
- Taylor, R.J. et al., "Convective Activity Above A Large-Scale Bush Fire," Australia, J. Appl. Meteorol., 12, 1144, October 1973.
- Teller, E., "Widespread Aftereffects of Nuclear War," Nature, 310, 621, 1984.
- Tewarson, A., "Experimental Evaluation of Flammability Parameters of Polymeric Materials," Flame-Retardant Polymeric Materials, Vol. 3, Lewin, Atlas, and Pearce, Eds., Plenum Press, New York, 1982.

Tewarson, A., "Physico-Chemical and Combustion/Pyrolysis Properties of Polymeric Materials," Factory Mutual Research Report, prepared for National Bureau of Standards, November 1980.

Turco, R.P., O. Toon, T. Ackerman, J.B. Pollack, C. Sagan, "Nuclear Winter: Global Consequences of Multiple Nuclear Explosions," Science, 222, 1283, 1983.

USDA Forest Service, "Forestry Smoke Management Guidebook," General Technical Report SE-10, December 1976.

U.S. Standard Atmosphere, published by NOAA, NASA, and USAF, 1976.

VanStraten, F. et al., "Preliminary Experiments Using Carbon Black for Cloud Modification and Formation," Naval Research Laboratory Report 5235, 1958.

Voice, M.E. and F.J. Gauntlett, "Picture of the Month: The 1983 Ash Wednesday Fires in Australia," Mon. Weather Rev., 112, 584, 1984.

Wang, W.C. et al., "Greenhouse Effects Due to Man-Made Perturbations of Trace Gases," Science, 194, 685, 1976.

Weast, R.C., Handbook of Chemistry and Physics, 62nd Edition, p. F-204, CRC Press, Boca Raton, Florida, 1981.

Wexler, H., "The Great Smoke Pall of September 24-30, 1950," Weatherwise, 3, 129, December 1950.

APPENDIX A

TASK ORDER



OFFICE OF THE UNDER SECRETARY OF DEFENSE

WASHINGTON D C 20301

RESEARCH AND
ENGINEERING

9 February 1984

TASK ORDER

NO. MDA903 84 C 0031: T-4-237

**TITLE: Atmospheric Injection and Scavenging of
Smoke Particles from Fires**

1. This task is for work to be performed by the Institute for Defense Analyses for the Defense Nuclear Agency.

2. BACKGROUND:

The current concern of major climatic cooling arising from a nuclear exchange is based largely on the scenario that nuclear detonations will ignite large fires. These fires produce a large quantity of fine smoke particles, which - when carried sufficiently high in the atmosphere - are claimed to produce cooling at the earth's surface. The altitude of the smoke cloud is alleged to determine whether cooling or warming occurs, while the rate of removal of the smoke particles will determine the duration of the climatic effects. An evaluation of the quantities of smoke particles, the rise height, and the scavenging rate is needed as a first step in determining the credibility of this scenario. To do so, data on different types of fires (urban, forest, oil, etc.) and on removal mechanisms and rates will be examined.

3. OBJECTIVE AND SCOPE:

To evaluate the magnitude of particulate injection, the rise height, and the rate of removal of smoke particles put into the atmosphere as a consequence of large-scale fires as posited to result from a massive nuclear exchange. The work will review current knowledge and uncertainties and make recommendations on how the uncertainties may be reduced.

4. SCHEDULE:

This effort will begin 1 January 1984. A draft document will be delivered by 30 September 1984, and a final version 90 days thereafter. Memoranda and briefings will be given as significant portions of the effort are completed.

5. TECHNICAL COGNIZANCE:

Technical cognizance for this task is assigned to the Director, Radiation Directorate, Defense Nuclear Agency, Attn: RAAE.

6. FUNDING:

The expenditure of \$74,000 of FY 1984 funds is authorized for this task.

7. SPECIFIC ADMINISTRATIVE INSTRUCTIONS:

a. If at any time during the course of this task IDA identifies the need for changes in this task, such as additional resources, schedule modification, changes to emphasis of effort or scope, etc., as set forth in the above paragraphs, a report with appropriate recommendations will be submitted in accordance with the terms of the IDA/WSEG Memorandum of Understanding of 12 March 1975 (and its successor) as applicable to the Director, DoD-IDA Management Office, OUSDRE, with a copy to the sponsor or his project officer, as appropriate. Changes in this task will be made only with the approval of appropriate cognizant DoD officials.

b. This task will be conducted under Industrial Security Procedures in the IDA area. If certain portions of the task require the use of sensitive information which must be controlled under military security, the DoD-IDA Management Office will provide supervised working areas in which work will be performed under military security control.

c. The termination date, the date after which no further costs will be incurred against the contract, for this task is 7 January 1985; unless changed by a written amendment to this task order.

d. A "need to know" is hereby established in connection with this task. Specifically, authority is granted to IDA to request, in my name, classified and unclassified documents and publications needed to accomplish this task and to verify, using my name, the "need to know" with respect to access to classified information needed to complete this task. Further, IDA authority to request

documents and publications and to verify "need to know" with respect to security clearances is restricted (1) to IDA members assigned in writing to work on this task and (2), to the duration of this task, as specified in the task order.



T. L. RICKETTS
Colonel USA
Director
DoD-IDA Management Office

ACCEPTED:



A. J. GOODPASTER
General, U.S. Army (Ret.)
President, Institute for Defense Analyses

DATE: February 17, 1984

APPENDIX B

A MODEL FOR SOOT PARTICLES, DESCRIBED AS SPHERES

APPENDIX B

A MODEL FOR SOOT PARTICLES, DESCRIBED AS SPHERES*

The soot-like aerosols used in the urban model of Shettle and Fenn (1979) are assumed to be spheres with the same size distribution as the rural aerosol model. The refractive index of soot-like aerosols was based on the soot data in Twitty and Weinman, 1971 (see Table B.1). The particle size distribution is given in Figs. B.1 to B.3 (for more data on other aerosols, see Shettle, Fenn, and Mill, in publication, December 1984).

*Source: E.P. Shettle and R.W. Fenn, "Models for the Aerosols of the Lower Atmosphere and the Effects of Humidity Variations on their Optical Properties," AFGL-TR-79-0214, September 1979.

TABLE B.1. REFRACTIVE INDEX FOR THE DIFFERENT AEROSOL COMPONENTS

WAVELENGTH (MICRONS)	WATER SOLUBLE	DUST-LIKE	SOOT	SEA SALT	WATER
2.000	1.510 -7.00E-02	1.530 -7.00E-02	1.500 -1.350	1.510 -1.00E-04	1.296 -1.15E-07
2.500	1.513 -3.00E-02	1.530 -3.00E-02	1.626 -0.453	1.510 -5.00E-06	1.262 -1.35E-06
3.000	1.510 -8.00E-03	1.530 -8.00E-03	1.748 -0.478	1.510 -2.00E-06	1.245 -1.45E-06
3.571	1.530 -5.00E-03	1.530 -8.00E-03	1.758 -0.460	1.510 -6.00E-07	1.245 -8.45E-09
4.000	1.530 -5.00E-03	1.530 -8.00E-03	1.758 -0.460	1.500 -2.00E-08	1.339 -1.00E-09
4.688	1.530 -5.00E-03	1.530 -8.00E-03	1.758 -0.450	1.500 -2.00E-08	1.335 -9.49E-10
5.145	1.530 -5.00E-03	1.530 -8.00E-03	1.758 -0.450	1.500 -1.00E-08	1.336 -1.00E-09
5.500	1.530 -6.00E-03	1.530 -8.00E-03	1.758 -0.444	1.500 -1.00E-08	1.333 -1.00E-09
6.320	1.533 -6.00E-03	1.530 -8.00E-03	1.758 -0.440	1.490 -2.30E-08	1.332 -1.00E-09
6.943	1.533 -7.00E-03	1.530 -8.00E-03	1.758 -0.430	1.490 -1.00E-07	1.331 -1.00E-09
7.500	1.520 -1.20E-02	1.520 -8.00E-03	1.758 -0.430	1.470 -2.30E-04	1.329 -8.29E-07
8.000	1.510 -2.00E-02	1.520 -8.00E-03	1.758 -0.440	1.470 -4.00E-06	1.323 -1.69E-05
9.000	1.510 -2.30E-02	1.500 -8.00E-03	1.770 -0.460	1.460 -6.00E-06	1.310 -9.07E-05
1.0000	1.463 -1.70E-02	1.530 -8.00E-03	1.770 -0.460	1.450 -8.00E-06	1.312 -1.15E-04
1.2000	1.421 -8.00E-03	1.520 -9.00E-03	1.810 -0.490	1.450 -1.00E-03	1.306 -1.15E-03
1.4000	1.420 -1.00E-02	1.520 -9.00E-03	1.810 -0.500	1.440 -2.00E-03	1.292 -3.98E-04
1.6000	1.420 -1.20E-02	1.500 -9.00E-03	1.820 -0.510	1.430 -4.00E-03	1.261 -1.74E-03
1.8000	1.400 -5.50E-02	1.500 -1.30E-02	1.810 -0.524	1.400 -7.00E-03	1.100 -1.54E-02
2.0000	1.420 -2.20E-02	1.500 -1.20E-02	1.800 -0.540	1.510 -1.00E-02	1.371 -0.272
2.2000	1.430 -7.00E-03	1.520 -1.00E-02	1.866 -0.544	1.490 -3.30E-03	1.478 -0.24E-02
2.5000	1.452 -5.00E-03	1.520 -1.10E-02	1.870 -0.550	1.480 -2.80E-03	1.422 -2.64E-02
3.0000	1.452 -5.00E-03	1.520 -1.10E-02	1.880 -0.563	1.470 -1.60E-03	1.406 -9.40E-03
3.5000	1.455 -5.00E-03	1.520 -1.20E-02	1.920 -0.570	1.460 -1.40E-03	1.359 -3.51E-03
4.0000	1.468 -1.50E-02	1.540 -1.40E-02	1.930 -0.580	1.450 -1.40E-03	1.351 -8.61E-03
4.5000	1.458 -1.20E-02	1.520 -1.60E-02	1.930 -0.593	1.450 -2.50E-03	1.325 -1.24E-02
5.0000	1.440 -1.00E-02	1.520 -2.10E-02	1.970 -0.600	1.470 -3.60E-03	1.292 -1.35E-02
5.5000	1.413 -2.30E-02	1.510 -3.70E-02	2.030 -0.620	1.410 -1.10E-02	1.245 -1.15E-02
6.0000	1.433 -2.30E-02	1.540 -3.90E-02	2.030 -0.625	1.600 -7.20E-02	1.363 -0.86E-02
6.5000	1.463 -3.30E-02	1.570 -4.20E-02	2.040 -0.630	1.600 -5.00E-03	1.335 -3.92E-02
7.0000	1.403 -7.00E-02	1.400 -5.50E-02	2.066 -0.650	1.420 -7.30E-03	1.312 -2.21E-02
8.0000	1.013 -1.100	1.130 -7.40E-02	2.130 -0.670	1.400 -1.30E-02	1.294 -2.29E-02
8.5000	1.303 -2.215	1.320 -9.00E-02	2.150 -0.690	1.420 -2.60E-02	1.266 -2.51E-02
9.0000	2.403 -2.290	1.400 -1.100	2.160 -0.690	1.400 -1.00E-02	1.272 -3.47E-02
9.5000	2.500 -3.370	1.470 -1.100	2.170 -0.700	1.400 -2.00E-02	1.262 -3.90E-02
10.0000	2.600 -4.420	1.520 -1.100	2.180 -0.700	1.400 -2.60E-02	1.255 -4.15E-02
10.5000	1.951 -1.160	1.730 -1.162	2.190 -0.710	1.400 -1.60E-02	1.243 -4.40E-02
11.0000	1.870 -9.50E-02	1.746 -1.162	2.230 -0.715	1.360 -1.60E-02	1.229 -4.75E-02
11.5000	1.820 -9.00E-02	1.750 -1.162	2.230 -0.720	1.560 -1.50E-02	1.210 -5.00E-02
12.0000	1.768 -7.00E-02	1.620 -1.128	2.220 -0.730	1.560 -1.40E-02	1.175 -6.74E-02
12.5000	1.720 -5.00E-02	1.620 -1.105	2.230 -0.733	1.400 -1.40E-02	1.152 -8.68E-02
13.0000	1.673 -4.70E-02	1.590 -1.100	2.240 -0.740	1.400 -1.40E-02	1.126 -1.102
13.5000	1.620 -5.30E-02	1.510 -9.00E-02	2.270 -0.750	1.420 -1.60E-02	1.123 -1.259
14.0000	1.620 -5.30E-02	1.470 -1.100	2.280 -0.763	1.410 -1.60E-02	1.146 -1.385
14.5000	1.568 -7.30E-02	1.520 -8.50E-02	2.310 -0.775	1.410 -2.30E-02	1.216 -1.770
15.0000	1.448 -1.100	1.570 -1.100	2.330 -0.790	1.400 -3.00E-02	1.254 -3.306
15.5000	1.420 -2.000	1.570 -1.100	2.360 -0.813	1.400 -9.00E-02	1.276 -4.627
16.0000	1.420 -2.000	1.570 -1.100	2.360 -0.813	1.500 -9.00E-02	1.306 -4.429
16.5000	1.758 -1.160	1.600 -1.100	2.360 -0.813	1.740 -1.120	1.386 -4.429
17.0000	2.000 -1.160	1.630 -1.100	2.380 -0.828	1.700 -1.136	1.423 -4.426
17.5000	2.000 -1.160	1.640 -1.115	2.400 -0.840	1.770 -1.135	1.463 -4.421
18.0000	1.900 -1.170	1.640 -1.115	2.410 -0.830	1.770 -1.135	1.463 -4.421
18.5000	1.850 -1.170	1.640 -1.115	2.410 -0.830	1.770 -1.135	1.463 -4.421
19.0000	2.120 -2.200	1.670 -1.220	2.460 -0.858	1.760 -1.152	1.400 -2.793
20.0000	2.000 -2.230	1.770 -2.200	2.460 -0.858	1.760 -1.152	1.400 -2.793
21.0000	2.000 -2.230	1.900 -2.200	2.460 -0.858	1.760 -1.152	1.400 -2.793
22.0000	2.000 -2.240	1.970 -2.240	2.510 -0.890	1.760 -1.152	1.400 -2.793
23.0000	1.800 -2.280	1.970 -2.240	2.510 -0.890	1.760 -1.152	1.400 -2.793
24.0000	1.800 -2.290	1.970 -2.240	2.510 -0.890	1.760 -1.152	1.400 -2.793
25.0000	1.800 -2.290	1.970 -2.240	2.510 -0.890	1.760 -1.152	1.400 -2.793
26.0000	1.800 -2.290	1.970 -2.240	2.510 -0.890	1.760 -1.152	1.400 -2.793
27.0000	1.800 -2.290	1.970 -2.240	2.510 -0.890	1.760 -1.152	1.400 -2.793
28.0000	1.800 -2.290	1.970 -2.240	2.510 -0.890	1.760 -1.152	1.400 -2.793
29.0000	1.800 -2.290	1.970 -2.240	2.510 -0.890	1.760 -1.152	1.400 -2.793
30.0000	1.800 -2.290	1.970 -2.240	2.510 -0.890	1.760 -1.152	1.400 -2.793
31.0000	1.800 -2.290	1.970 -2.240	2.510 -0.890	1.760 -1.152	1.400 -2.793
32.0000	1.800 -2.290	1.970 -2.240	2.510 -0.890	1.760 -1.152	1.400 -2.793
33.0000	1.800 -2.290	1.970 -2.240	2.510 -0.890	1.760 -1.152	1.400 -2.793
34.0000	1.800 -2.290	1.970 -2.240	2.510 -0.890	1.760 -1.152	1.400 -2.793
35.0000	1.800 -2.290	1.970 -2.240	2.510 -0.890	1.760 -1.152	1.400 -2.793
36.0000	1.800 -2.290	1.970 -2.240	2.510 -0.890	1.760 -1.152	1.400 -2.793
37.0000	1.800 -2.290	1.970 -2.240	2.510 -0.890	1.760 -1.152	1.400 -2.793
38.0000	1.800 -2.290	1.970 -2.240	2.510 -0.890	1.760 -1.152	1.400 -2.793
39.0000	1.800 -2.290	1.970 -2.240	2.510 -0.890	1.760 -1.152	1.400 -2.793
40.0000	1.800 -2.290	1.970 -2.240	2.510 -0.890	1.760 -1.152	1.400 -2.793

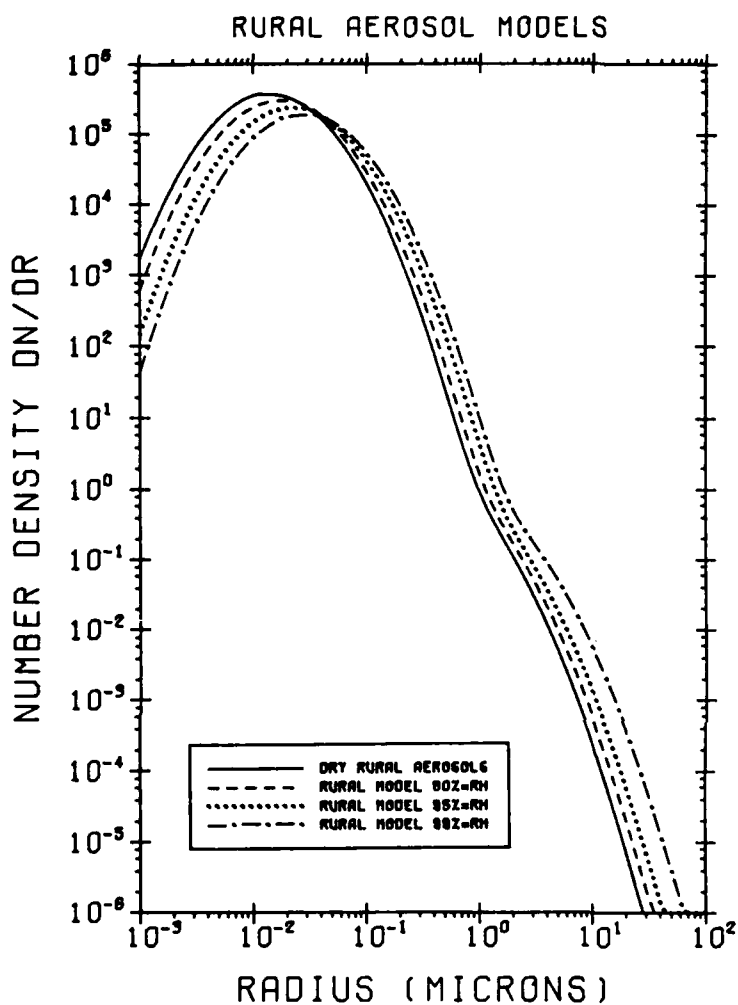


FIGURE B-1. Aerosol Number Distribution ($\text{cm}^{-3} \mu\text{m}^{-1}$) for the Rural Model at Different Relative Humidities with Total Particle Concentrations Fixed at $15,000 \text{ cm}^{-3}$.

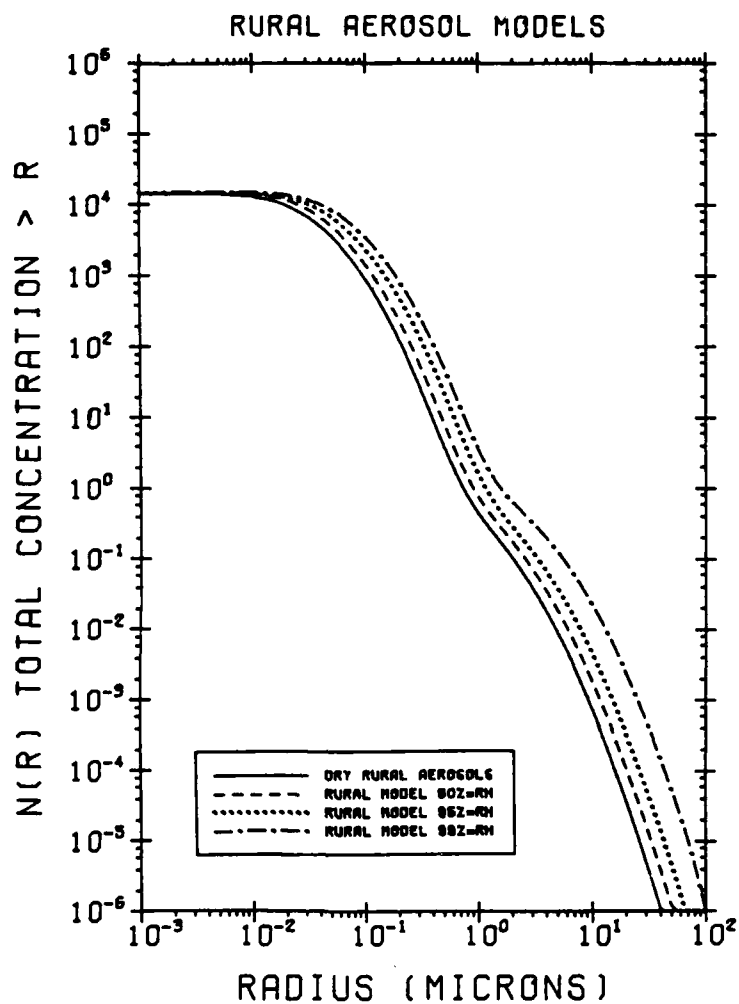


FIGURE B.2. Cumulative Number Density (cm^{-3}) for the Rural Aerosol Model at Different Relative Humidities with Total Particulate Concentration Fixed at $15,000 \text{ cm}^{-3}$.

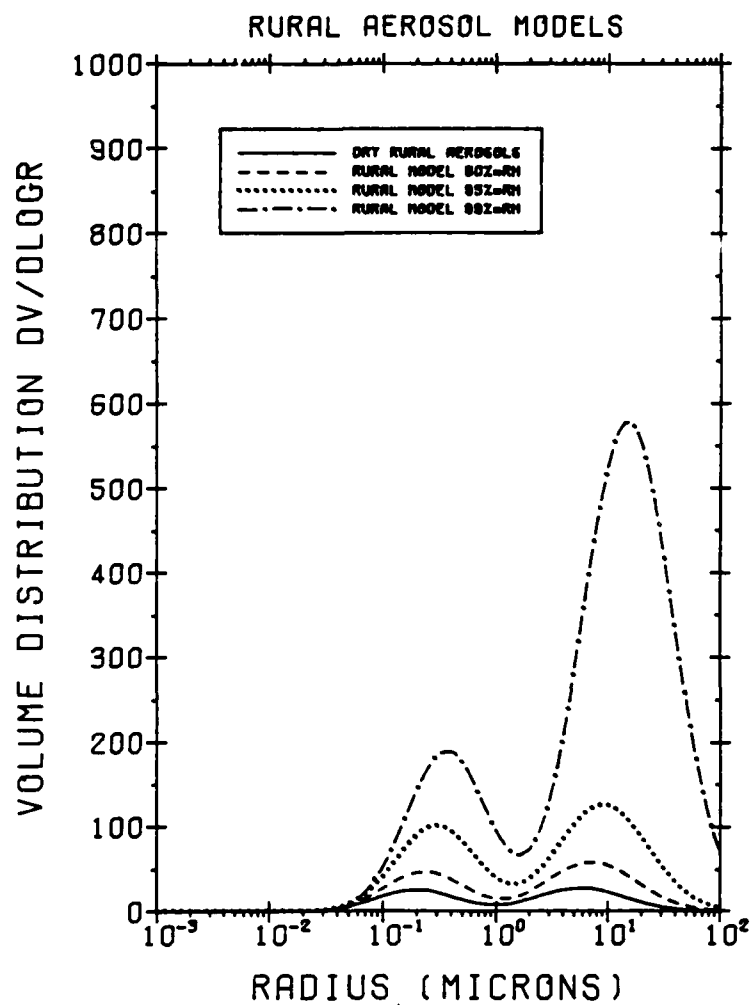


FIGURE B.3. Volume Distribution ($\mu\text{m}^3/\text{cm}^3$) for the Rural Aerosol Model at Different Relative Humidities with the Total Particle Concentration Fixed at $15,000 \text{ cm}^{-3}$.

APPENDIX C

NUCLEAR-INDUCED FIRES; ATMOSPHERIC/CLIMATE EFFECTS
DUE TO MOLECULAR GASES

APPENDIX C. NUCLEAR-INDUCED FIRES; ATMOSPHERIC/CLIMATE EFFECTS DUE TO MOLECULAR GASES

When wood (or similar material) burns in air, a variety of minor species are produced in addition to CO_2 , H_2O , and soot. Page 2-5 lists some of the materials produced. The impact of these minor species on the atmosphere is indicated in Chart C.1, which is based on the following assumptions:

1. City fire burns 4×10^6 tons wood
2. Scenario = 1000 city fires

Note the large emissions of CO , NO_x , and hydrocarbons.

What are the effects of these molecules? CO is fairly long-lived; it destroys OH but has no large greenhouse effect. NO_x produces ozone in the troposphere and destroys it in the stratosphere (see Penner, 1983). Hydrocarbons will destroy OH and (in the troposphere) may produce ozone if there is enough NO_x and sunlight--but they will certainly give rise to a greenhouse warming. The volatile organic compounds listed on page 2-5 are either hydrocarbons or else more reactive organic molecules which would tend to be photolyzed rather rapidly by any solar UV radiation that penetrates into the smoke cloud.

Chart C.2 gives relevant IR optical properties of some simple hydrocarbons, their "greenhouse effectiveness" $\partial T / \partial M$ from Wang et al. (1976) and also the computed greenhouse warming due to CH_4 and C_2H_4 , assuming the mass injections of Chart C-1. For whatever this scaling is worth, the greenhouse warming is reasonable but not terribly large; the "band sum" (absolute intensity or f-number) for the various molecules is not too different, so that presumably the effects of the various other molecules that have transitions in the 7-14 μm spectral range

will be comparable. The total greenhouse warming might be several degrees for a scenario of 10,000 rather than 1000 city fires.

Thus, what photochemical and climatic perturbations may be expected, in addition to the soot-injection-induced "Nuclear Winter" cooling?

1. Substantial changes in NO_x and in ozone, in particular in the stratosphere, largely as a result of bomb-induced NO_x injection of the fireball rather than from fires (see Chart C-1).
2. A fairly small greenhouse warming ($\lesssim 1^\circ\text{K}$); see Chart C-2.
3. Substantial enhancement of CO in the troposphere.
4. Substantial enhancement of hydrocarbons in the troposphere.
5. A probably quite short-lived injection of exotic organic compounds giving rise to "tropospheric smog."
6. A small fractional enhancement in atmospheric CO_2 .

Of these, the photochemical effects 1 and 5 depend on the presence of sunlight, i.e., they will not occur under a severe smoke pall, but presumably they have to be considered whenever the soot has disappeared. In the presence of sunlight, a potentially significant consequence of items 3, 4, and 5 may be a reduction in atmospheric OH radical which, in turn, may lead to a variety of photochemical consequences.

CHART C.1. ATMOSPHERIC LOAD AND PERTURBATION OF VARIOUS MINOR SPECIES

Species	Ambient Atmospheric Loading (kg)	Fire Emission Index assumed (g/kg)	Atmospheric Injection (kg)
CO ₂	2.1x10 ¹⁵ 1	1300	5.2x10 ¹²
H ₂ O	7.1x10 ¹⁵ 2	500	2.0x10 ¹²
CO	8.0x10 ¹¹ 1	65	2.6x10 ¹¹
NO _x (as NO ₂)	1.0x10 ¹⁰ 1	4	1.6x10 ¹⁰
		5.3 kt/Mt due to fireball: 5.3x10 ¹⁰	due to fire, in troposphere in stratosphere, from fireball
		10,000 Mt	
CH ₄	3.6x10 ¹² 3	25	1.0x10 ¹¹
C ₂ H ₄	8.4x10 ⁸ 3	5	2.0x10 ¹⁰
O ₃	2.9x10 ¹² 2		
		large, due to photochemistry- see Penner (1983):	
		net decrease in column and stratosphere, increase in troposphere	

* Mass of atmosphere = 1.225 (kg/m³) x 5.1x10¹⁴ (m²) x 7x10³ (m) = 4.37x10¹⁸ kg

¹ See USSA (1976), p.33- I assume 1.5 ppbv of NO_x

² Bauer (1984), p.26

³ See Wang et al (1976), Table 3.

CHART C.2. OPTICAL AND GREENHOUSE PROPERTIES OF SOME MOLECULES

Molecule/vibration	$\nu(\text{cm}^{-1})$	absorption range (μm)	Band ₂₀ sum ₁ $10^{-20}\text{cm}^{-1}/(\text{mol. cm}^{-2})$	$\partial T/\partial M_2$ ($^{\circ}\text{K/kg}$) ²	ΔT due to canonical injection from Chart
CH_4 / ν_4	1306	6.5-9.2 / 7.66	520 ¹	6.6×10^{-12}	0.66
$\text{C}_2\text{H}_2 / \nu_5$	730	12.3-15.4/13.7	2980 ³	--	
$\text{C}_2\text{H}_4 / \nu_7$	949	/10.5	1320 ⁴	1.2×10^{-11}	0.24
$\text{C}_2\text{H}_6 / \nu_9$	822	10.7-13.9/	145 ³	--	
O_3 / ν_3	1042	8.2-10.3/9.6	1260 ¹	1.6×10^{-13}	-0.23 (for 50% ozone reduction)

¹Rothman et al (1981)

²Wang et al(1976)

³Rothman et al(1983)

⁴Golike et al (1956)

APPENDIX D

ON THE WINCHESTER, VIRGINIA TIRE FIRE OF NOVEMBER 1983
see also Culkowski et al. (1984)

River Protected From Oil Oozing Out of Burning Mound of Tires

By Philip Smith
Washington Post Staff Writer

So far 685,000 gallons of an oily, rubbery, brownish liquid has oozed from a mountain of burning tires in rural Virginia, but thanks to \$1.3 million from the Environmental Protection Agency's Superfund and the efforts of hundreds of workers and scientists more of it has reached the Potomac River, officials said yesterday.

"If it weren't for the EPA," said a spokesman for Virginia's Office of Emergency and Energy Services, "I don't know what the hell we would have done."

The officials credited the federal fund with enabling them to contain the oil-and-water ooze from 4 1/2 acres of tires near Winchester in early November.

But the officials concede they still are baffled about how to extinguish the fire which they say was probably deliberately set and went up a dark plume visible from three states. The mound of burning tires are owned by Paul Blumhardt, an elderly farmer who had begun building an incinerator to smelt them when the fire broke out.

The 685,000 gallons (of runoff) we've picked up would have ended up floating down the Potomac," said Joseph LaFornara, chief chemist of EPA's National Environmental Response Team, from the scene.

The runoff is flowing from the bottom of a

See OOOZE, B7, Col. 4



Firefighters working protective units light flames around burning tires near Winchester, Va.



A heavy-duty high-power pump called "Fire Fly" sprays water from a pond on field where tires mysteriously burst last November in early November.

OOZE, From B1

small mountain of used tires now estimated to number 8 million. Left unchecked, state and EPA officials said the one would have entered an unnamed tributary nearby, then Hogue Creek in Frederick County and could have endangered the Potomac.

Scientists inserted a 15-foot water pipe into the mound's burning core on Thursday. "It momentarily cooled the fire," LaFornara said yesterday. "When we took the water away, it started cooking again."

"The damaged pipe melted," said Michael LaCivita, a state emergency services spokesman.

Meanwhile, LaFornara said, the amount of runoff abate and from daily, for reasons that are unknown. "Some days it's out or seven gallons a minute," he said. "Other days it's a couple hundred gallons a minute. When it decides to burp, it burps."

Estimates of how long the fire may last, smoldering under an outer crust of molten rubber, range from 60 days to a year, officials said yesterday.

LaFornara said that the onset of cold weather was not expected to impede the fire. "It was in the teens

here this morning," he said, "and as burning away."

To capture the runoff, workers dug a ditch around three sides of the hillside site. The ditch channels the ooze to a central collection ditch lined with stone. From that point, where scientists have been measuring the flow and temperature of the oil and water mixture, the liquid is collected in a 300,000 gallon, rubber-lined containment basin.

Officials first paid contractors to haul the ooze away to a recycling plant in Cleveland. More recently they arranged for a private firm using its own trucks to remove the liquid for recycling in Fayetteville, Pa.

From the 685,000 gallons removed from the site, about 600,000 gallons of "fairly good quality" oil has been extracted, said LaFornara. EPA receives between 30 and 40 cents a gallon for the oil, which it is applying to the cost of the Winchester operation.

"We don't usually get a usable product from a hazardous waste site," LaFornara said. "It's an anomaly."

Remuneration on what to try next occupy daily meetings in command trailers at the site, where fire-watchers are on duty 24 hours. As many as 250

women, scientists, officials and military personnel have been on the scene in a single day since the fire began.

Members of the Coast Guard's Atlantic Strike Team monitor the area for pollution. Navy personnel are manning a Fire Fly pump, a device that pumps 3,000 gallons of water a minute and is being used to lower the water level in a nearby polluted pond in danger of overflowing.

Advice has been sought or received from the American Petroleum Institute, major tire manufacturers, professional fire fighting organizations and even private firms, including two in Texas that specialize in extinguishing blazing oil rigs.

As for solutions, said LaFornara, "A lot of people claim they've got it. But when push comes to shove and they see this place, they say 'we thought it was the size of somebody's garage.'"

The fire, meanwhile, has spawned souvenirs, including a membership card. "I survived Mount St. Helens," said a buyer. "Among the buyers was Miley Saville, a spokeswoman for the Virginia emergency services office who spent a wearying three weeks on the site.

"I think I survived it," she said.

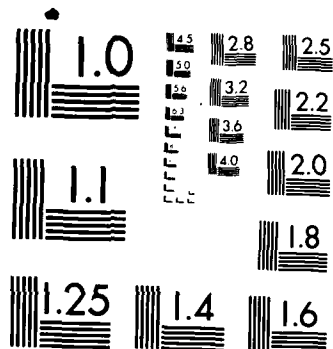
From Washington Post, 3-12-83

APPENDIX E

SOME THOUGHTS ON ARCTIC HAZE

AD-A161 807 NUCLEAR WINTER: SMOKE GENERATION DEPOSITION AND REMOVAL 2/2
(U) INSTITUTE FOR DEFENSE ANALYSES ALEXANDRIA VA
E BAUER DEC 84 IDA-M-24 IDA/HQ-84-29173
UNCLASSIFIED MDA903-84-C-0031 F/G 18/3 NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A



SCIENCE AND
TECHNOLOGY DIVISION

INSTITUTE FOR DEFENSE ANALYSES

1801 N. Beauregard Street, Alexandria, Virginia 22311 • Telephone (703) 845-2000
-2290

20 September 1984

Dr. Russell C. Schnell,
Project Scientist, AGASP,
Cooperative Institute for Research in Environmental Sciences,
University of Colorado,
Boulder, CO 80309.

Dear Russell:

Thank you very much for sending me information and reprints on ozone variations associated with layers of arctic haze (AH) during AGASP, following our recent telcon. I present here some thoughts on how AH/AGASP might help with the Nuclear Winter (NW) problem, which I'm sending also to a few other people. Comments and criticisms would be most welcome.

1. One question- which is being addressed in the laboratory by Bob Fristrom of APL- is how rapidly soot is destroyed by reaction with ozone (bearing in mind that "soot" isn't a well-defined chemical material). As you point out (Schnell & Raatz (1984)-GRL- see attachment I) "multiple layers of AH, varying in thickness from a few tens to hundreds of meters, were observed throughout the troposphere", but the results (see, eg Fig. 1, op cit, shown in att. I) show much less variability in ozone than in extinction cross section, CN, and particle concentration.

Now, the time scale for atmospheric motions on a distance d_v is of order

$$(1) \quad t_s = d_v^2 / 2K_v$$

where $K_v \sim 5 \text{ m}^2/\text{sec}$ (NOAA/ARL- Pack, Draxler, et al), which gives $t_s \lesssim 1 \text{ hour}$, from this one can only say that either

- (i) the ozone instrument is significantly less sensitive than the others shown in Fig. 1, or
- (ii) there is far more ozone in the troposphere than is needed to destroy the soot particles in AH, or
- (iii) the reaction between AH soot and ozone has a characteristic time much greater than t_s

You presumably can answer (i), I sort of doubt whether (ii) holds, and would not be surprised if (iii) were true. The ultimate question is- can one learn anything else about the soot-ozone reaction from AH/AGASP?

2. As you indicated, AH may have a representative travel time of 7-14 days in getting from its ground-level source in Siberia to where it was observed in Alaska, ie a distance of several thousand kilometers, at fairly constant latitude. (The proviso about constant latitude may be significant because it implies that except for the effect of local weather/fronts etc, which may raise it by several hundred meters in moving along an isentropic trajectory there is no normal meteorological/dynamic mechanism for lifting the haze layers from the surface to where they were observed in the middle troposphere). Thus I ask, can solar absorption-induced buoyancy lift the haze layers to where they were found. I calculate as follows.

The absorption optical thickness of haze in vertical viewing is $\tau_{av} \sim 0.02 - 0.05$ (Hal Rosen, private communication at NBS), and thus for an air mass of horizontal area A, the solar energy absorbed in time t_a is

$$(2) \quad E_{abs} = H_0 \epsilon A t_a$$

where $H_0 = 1.4 \text{ kw/m}^2$ (solar constant)
 $\epsilon =$ emissivity/absorptivity of AH layer in visible,
 $\epsilon \approx \tau_{av}$

Now, if this energy goes to raise an air layer of thickness d_v by a height Δh_a , so that

$$(3) \quad E_{buoy} = E_{abs} = A d_v \rho g \Delta h_a$$

where $\rho =$ air density $\approx 1 \text{ kg/m}^3$
 $g =$ acceleration due to gravity, 10 m/sec^2
 so that

$$(4) \quad h_a = (H_0 \tau_{av} / d_v \rho g) t_a$$

and for a layer of thickness $d_v = 500 \text{ m}$ and an insolation $t_a = 6 \text{ hours}$ per 24 hour interval, if $\tau_{av} = 0.05$ $\Delta h_a = 300 \text{ m}$ per 24 hours.

This is very crude, but clearly demonstrates that solar heating can raise the soot layer to heights of a few kilometers in 7-14 days. (Recall that for soot the emissivity in the visible is an order of magnitude greater than in the thermal IR, so that cooling at night- and subsequent sinking- will be an order of magnitude less than rising in the daytime).

The question here is

(i) is this discussion correct?

(ii) can any of this be observed and studied experimentally with past or future AGASP missions?

3. A "final" question is- what can one learn about precipitation scavenging from AH/AGASP? You mentioned some preliminary data on washout over Greenland (?).

Incidentally, could you send me a preprint of Raatz' article for Tellus on the Ptarmigan flights, and also your Atms. Envir. article on Air Mass Characteristics doesn't include Fig. 5 which is listed in the text.

Sincerely yours,

A handwritten signature in cursive script, appearing to read 'Ernie', with a horizontal line drawn underneath it.

Ernest Bauer

cc- Dr. Art Aikin, NASA/GSFC
Dr. Jim Angell, NOAA/ARL
Dr. Bob Fristrom, APL
Dr. Ruth Reck, GMRL
Dr. Hal Rosen, LBL
Dr. Lee Wittwer, DNA/RAAE

VERTICAL AND HORIZONTAL CHARACTERISTICS OF ARCTIC HAZE DURING AGASP: ALASKAN ARCTIC

R. C. Schnell¹ and W. E. Ranz²

¹CIRES, University of Colorado, Boulder, CO 80309

²Geophysical Monitoring for Climatic Change, Air Resources Laboratory, NOAA, Boulder, CO 80303

Abstract. Vertical and horizontal distributions of ozone, extinction due to aerosol light scattering, condensation nucleus concentrations, aerosol spectra, and meteorological parameters were measured with a NOAA WP-3D research aircraft over the Alaskan Arctic in March 1983. Multiple layers of haze, varying in thickness from a few 10's to 100's of meters, were observed throughout the troposphere. A maximum concentration of aerosols was located between 600 and 800 mb. Distribution of the haze layers was associated with distinct meteorological boundaries. The characteristics of the haze changed in response to stages in the progression of a major Arctic haze episode. On March 17, 1983, the Arctic anticyclone was penetrated and its meteorological and aerosol properties determined.

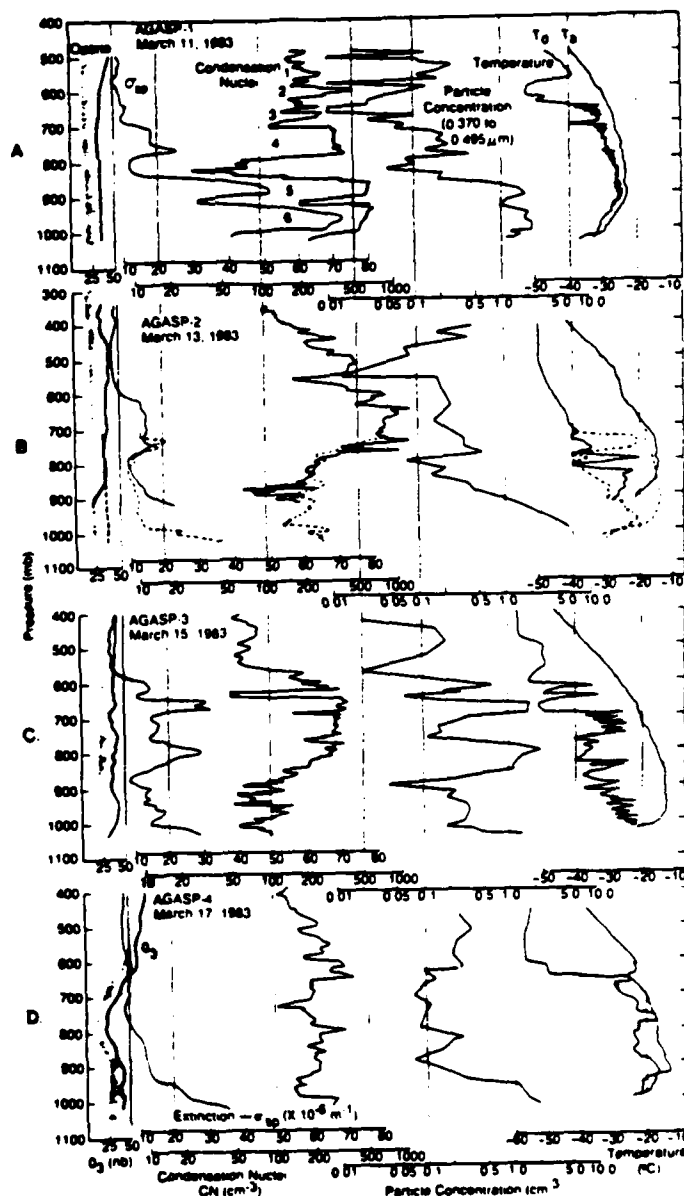


Fig. 1. Ozone, σ_{sp} , condensation nuclei, large-particle concentrations (0.370 to 0.495 μ diameter) and temperature-dewpoint profiles upwind of Barrow, Alaska, A) Descending, 2134 to 2226 UT. B) Lower portion, descending (dashed line), 2204 to 2240 UT, March 13; upper portion, ascending (solid line), 0232 to 0258 UT, March 14. C) Descending, 2224 to 2318 UT, March 15. D) Descending, 2234 to 2325 UT, March 17.

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NATIONAL OCEANIC AND
ATMOSPHERIC ADMINISTRATION

October 10, 1984

Dr. Ernest Bauer
IDA
1801 N. Beauregard Street
Alexandria, VA 22311

Dear Dr. Bauer:

Thank-you for your letter of September 20, 1984 and the analyses therein.

With respect to the ozone-soot reaction, Mr. Sam Oltnans our resident ozone expert suggests that your point (iii) is the most probable. You had already suggested this was the case.

As to the haze lifting mechanism, there is evidence from airborne lidar measurements that the haze layers have a definite slope to them, rising as one moves north. Dr. Pat McCormick, NASA Langley, FTS 928-2065, has excellent data showing this effect. Given a bit of incentive (political and/or monetary) NASA could fly the system in conjunction with the 1986 AGASP program.

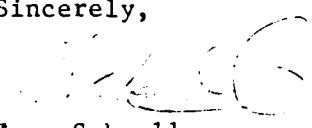
As to the washout of haze, we flew south off Spitzbergen from the ice to open sea. In this area, the haze becomes incorporated in the marine boundary layer and clouds and then appear to be removed. We have in-situ data on this process but have not studied it in any great detail as our interests were otherwise engaged. I cannot give a good answer as to the overall quality or amount of data that we have in hand.

If the interest were there, I could pass through it lightly in a few weeks.

We could of course do a more thorough job in AGASP-II whenever there was flow from the north off the ice.

I have enclosed a copy of Raatz's Ptarmigan paper along with 2 others on haze. The "Airmass Characteristics ..." is a new version; discard the one sent previous. The ozone intrusion paper should be of interest to the ozone-haze removal research community.

Sincerely,


Russ Schnell
Director, AGASP

APPENDIX F

MORE INFORMATION ON THE CANADIAN FOREST FIRES OF SEPTEMBER 1950

APPENDIX F

MORE INFORMATION ON THE CANADIAN FOREST FIRES OF SEPTEMBER 1950

F.1 GENERAL DESCRIPTION OF THE FIRES

Letter dated 11 July 1984 from Dean Peter J. Murphy,
University of Alberta, to C. Bently Lyon, U.S. Forest Service
(pages F-4 through F-7).



July 11, 1984

Mr. C. Bentley Lyon
Staff Fire Control Technologist
Forest Fire and Atmospheric
Sciences Research
United States Department of
Agriculture, Forest Service
12th & Independence S.W.
P.O. Box 2417
Washington, D.C.
20013

Dear Mr. Lyon:

Dennis Dube sent over a copy of your May 14 letter to Peter Paul asking about the September 1950 fires. That indeed was a time of major blowup and I have been trying to piece together the story for some years on an as-time-permits basis.

The photo enclosed shows the perimeters of the burns as nearly as I can determine them using data from fire reports in British Columbia and satellite imagery. The total area of burn is about 4 million acres. There is some question about the burn in the hatched area in the extreme northeast. Some accounts indicated that the fire ran around the community of Keg River, the Town having been saved by backfiring, and that it ran to the Peace River. I have a feeling that part of the burn occurred a few years later, but have not had a chance to visit on site to look for fire scars or to interview a number of the people. That is the area just above the letter A. I have lettered some other points for reference.

The major fire started at point B June 1, 1950. The ranger arrived the next day, found it was burning in/, approximately 250 acres in size and out of control. The feeling was that area would be developed for agriculture so it was decided not to take action. It burned throughout the summer, and the fire report from British Columbia showed the boundary stopping just west of the Alberta border. The fire at E started August 26, 1950. An Alberta fire report states that a ranger was sent out on horseback north of Eureka River to check to see if those fires were threatening Alberta. From about point C he reported that on September 2 or 3 the fires were "well inside" British Columbia. It is probable that during the blowup days of September 22-24 fires B and E joined together to burn

...2

out the Chinchaga River Valley. It is difficult to state, but the fires may have averaged 30 miles of advance per day during those three days, and on a pretty wide front.

The fire at D started July 29 but made its major run during the blowup period as well. That one reached about 300,000 ac.

I have learned more recently that there were other fires burning during that period. There were several small ones at F which were being fought at the time of the blowup and which were held, although with some difficulty. The fire at G was about 46,000 acres, H was 12,000 acres, and the one at I covered about 90,000 acres. My estimate of area burned did not include the last ones - F to I.

I have weather data from several of the federal stations around there and want to try some fire growth models to try to get a better estimate of possible daily travel distances, but that will have to wait a few more months.

From your letter I gather that you are aware of the references in meteorological journals - the Marine Observer, July 1951, and Weatherwise December, 1950.

The area in which those fires burned was typical of the northern Boreal forest with a variety of age-classes. However, the Chinchaga River Valley itself was renowned for its great timber-quality spruce. The fire evidently burned with a high intensity, and vegetative recovery on much of the area burned during the blowup period has been slow to regenerate, and even to revegetate in some places.

Our Forest Inventory program in Alberta began in 1949. Vertical area photographs were taken over the Chinchaga Valley during the early summer of 1950. Unfortunately, I have not been able to obtain funding to get someone to work on a comparison of forest cover types in there so cannot give you any estimates of biomass consumed.

My intention is to write this up for publication after I have attempted the modeling based on the weather data and the fire weather index components which may be derived from it. I wish I had it available to send you now.

.../3

- 3 -

I will be interested to learn how your compilations
turn out.

Sincerely,

Peter J. Murphy
Associate Dean - Forestry

PJM:db

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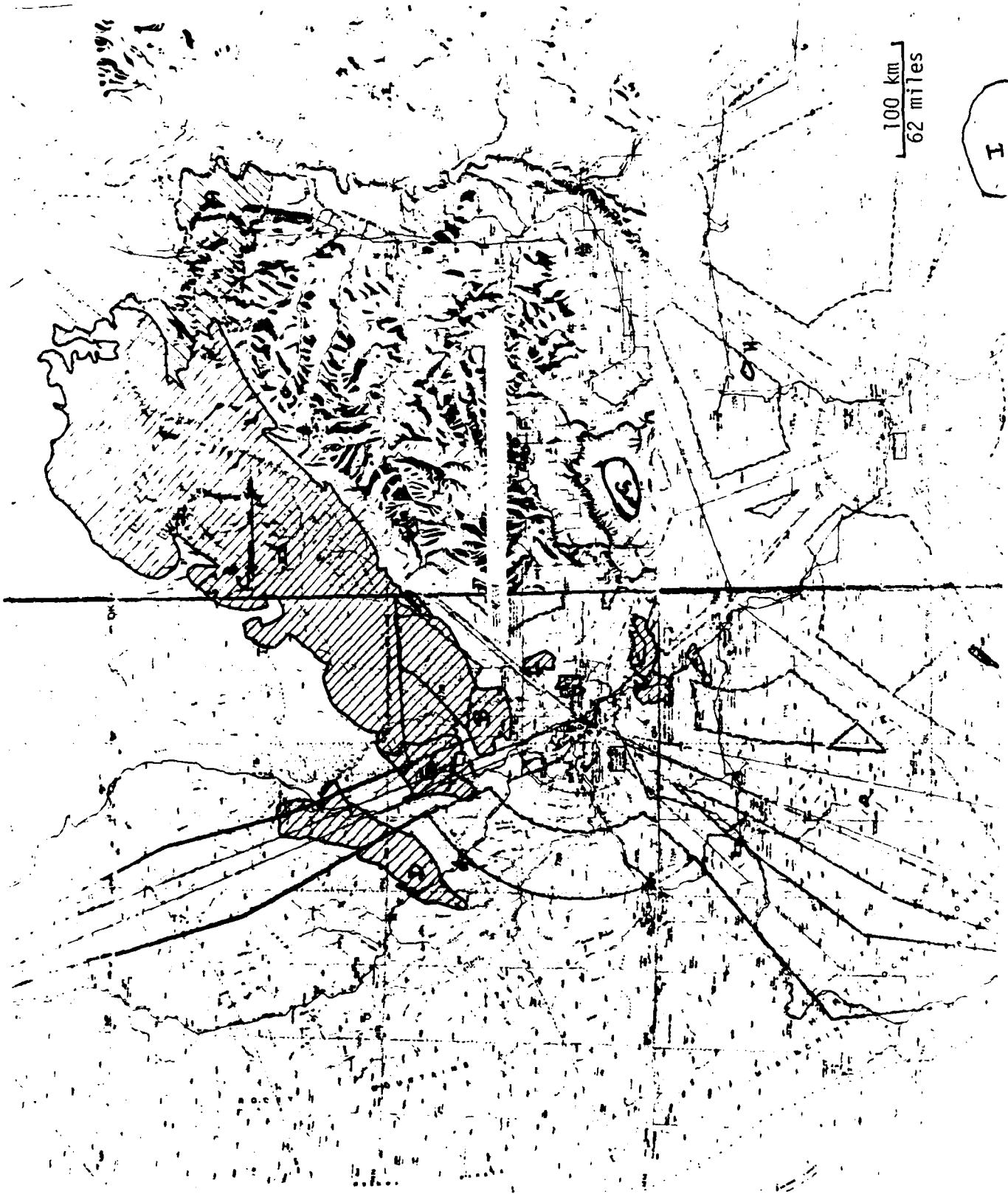


FIGURE F.1. Area of the Fires (Scale 1:500,000)

F.2 HOW DO THE NUMBERS FIT TOGETHER?

The basic data on transport are taken from p. 5-7 (from Smith, 1950) which is replotted as Fig F.2 with inferred center of mass points shown as \odot at designated times. Dispersion distances are estimated from an assumed starting point at 1300/22.

Longitudinal and transverse dispersion distances are plotted in Fig. F.3. Generally, σ (long) $>$ σ (trans), as one would expect, since longitudinal dispersion is due to large-scale convection. Overall, one sees that σ (trans) exceeds the upper bound IV of Fig. F.3 by a factor of less than 2.

Penndorf (1953) interprets the blue sun/blue moon data in terms of particles of mean radius $\bar{a} = 0.6 \mu\text{m}$ (0.5 to 0.8), of number density $n \sim 150/\text{cm}^2$ (128-175), and of column density $\sim 5.3 \times 10^7 \text{ part./cm}^2\text{-column}$ (4.7 - 6.5), corresponding to a vertical layer thickness $\Delta h = 3.5 \text{ km}$.

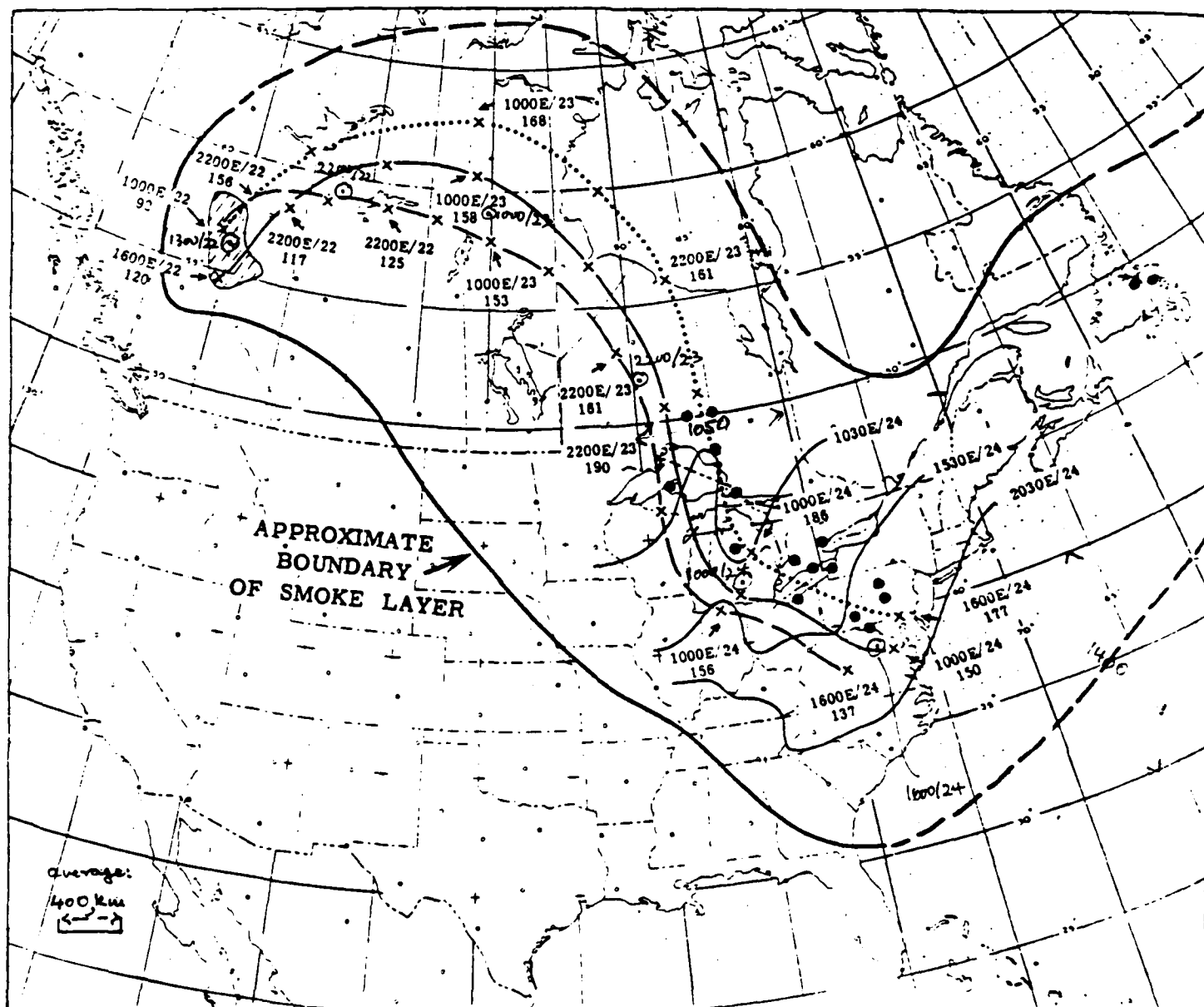
Note that this corresponds to an optical thickness

$$\xi = n \sigma_{\text{ext}} \Delta h \approx 1.1 ,$$

where $\sigma_{\text{ext}} = 2\pi\bar{a}^2$; this seems large. My estimate would have been $\xi \sim 0.1$.

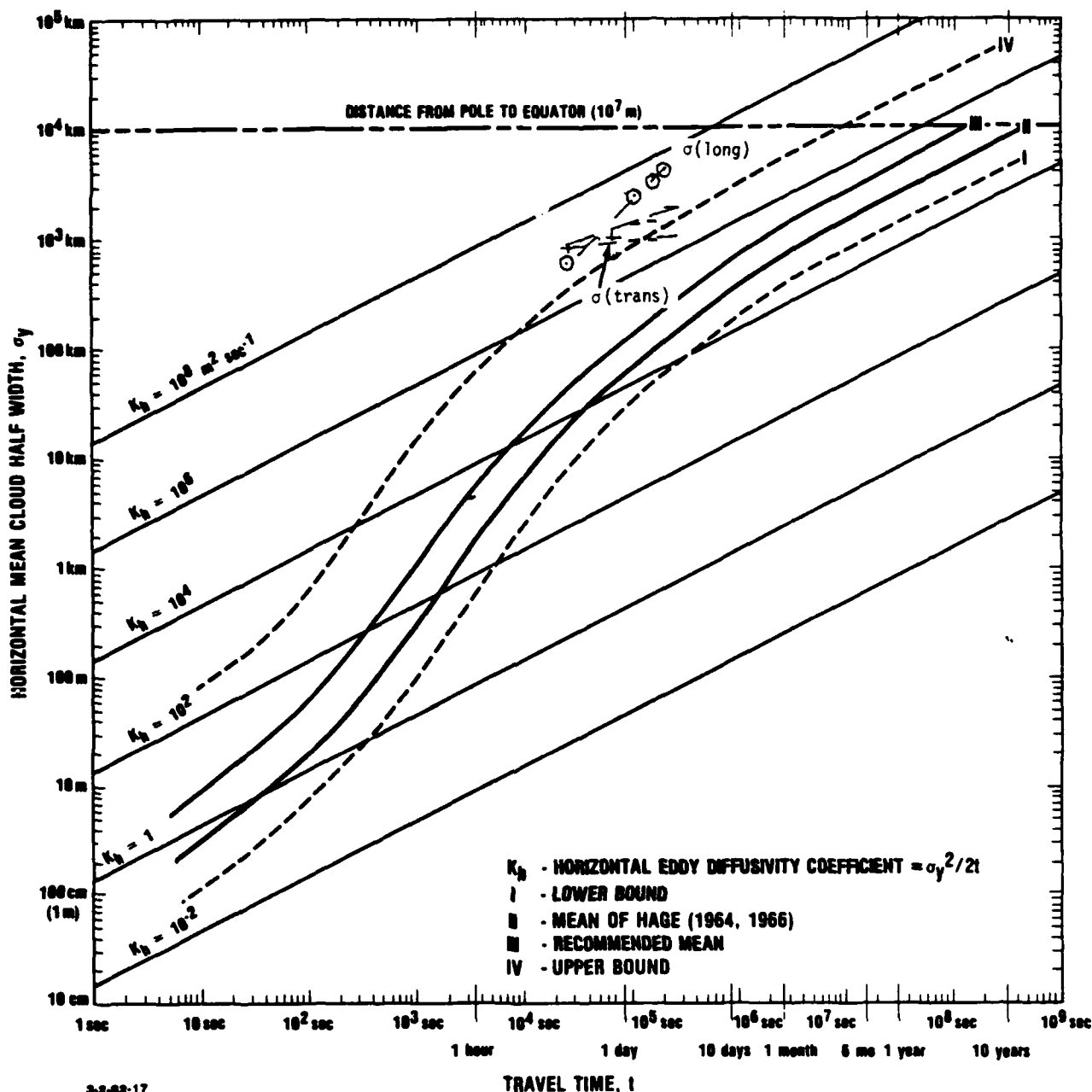
From Figs. F.2 and F.3 the horizontal cloud extent at 1000/24 is 2600 km. Thus, the cloud volume is $2 \times 10^{22} \text{ cm}^3$, mass per particle of $9 \times 10^{-13} \text{ g}$ and the total mass of smoke/soot is $3 \times 10^6 \text{ tonnes}$.

From Section F.1 above, the general area of forest fires is $4 \times 10^6 \text{ acres} = 1.6 \times 10^6 \text{ ha}$. With a fuel loading of 20 kg/m^2 and 10 percent of the fuel burned, this gives a fire loading for black spruce of 2 kg/m^2 (C. Chandler, private communication). If the soot is 1 to 3 percent of the total mass of fuel burned, this gives a soot mass of 0.3 to $1 \times 10^6 \text{ tonnes}$, which is in very adequate agreement with the previous estimate.



Source: Smith, 1951

FIGURE F.2. Trajectories of Air Parcels Calculated on Isentropic Charts of $\theta = 312^\circ \text{ A}$.



Source: Bauer, 1983

FIGURE F.3. Horizontal dispersion as a function of Travel Time. The mean curves and bounds apply to atmospheric altitudes up to 20 to 25 km. Earlier estimates of Hage (1964) and Hage et al. (1966) indicated slower spreading than do the more recent data. Thus, at present, the mean curve III with bounds I and IV is recommended as against the Hage's mean curve II and bounds I and III. The points σ_{long} and σ_{trans} come from Fig. F.2.

APPENDIX G

METEOROLOGICAL SCALES OF ENERGY

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1. This material is presented for general orientation, to show how large the meteorological scales of mass and energy are, even as compared to a very large nuclear engagement with

$$E_{\text{nuc1}} = 10,000 \text{ Mt} = 4.2 \times 10^{19} \text{ joule} \quad (\text{G.1})$$

All the numbers given here are representative rather than definitive. They refer to typical changes in a "meteorological air mass" as it changes from a cold to a warm air mass.

2. The linear dimension of a canonical air mass is taken as $d = 1000 \text{ km}$; its mass M_0 may be determined as follows: The atmospheric mass per unit area at sea level is $m = P_0/g$ where $P_0 = 1 \text{ atmosphere} = 1.013 \times 10^5 \text{ N/m}^2$ and g (acceleration due to gravity) $= 9.81 \text{ m/sec}^2$ so that $m = 1.03 \times 10^4 \text{ kg/m}^2$. The air mass is taken as containing 80 percent of this total, roughly equivalent to the tropospheric mass, so that

$$M_0 = m d^2 \times 0.8 = 8.2 \times 10^{12} \text{ tonnes} \quad (\text{G.2})$$

(Since the surface area of the earth is $5.1 \times 10^{14} \text{ m}^2$, an air mass corresponds to 5 percent of the total mass of the troposphere.)

3. A "warm" air mass is taken as 10°C warmer than a "cold" air mass, and it may contain an additional $2 \text{ g H}_2\text{O/kg air}$ (at

1 atmosphere pressure and 10°C, the saturation mixing ratio for moisture is 7.5 g H₂O/kg air--or 3.8 g H₂O/kg air at 0°C). To raise the temperature of air by 10°C at constant pressure takes an energy $c_p \Delta T$ per unit mass, and

$$c_p = (7/2)(R/M) = 10^3 \text{ joule/kg } ^\circ\text{C} \quad (\text{G.3})$$

since $R = 8.3 \text{ joule/g-mole } ^\circ\text{C}$ and $M = 29 \text{ g}$. Thus, for a mass M_0 the thermal energy due to just heating the dry air at constant pressure is

$$E_{th} = M_0 c_p \Delta T \sim 8.2 \times 10^{19} \text{ joule} \quad (\text{G.4})$$

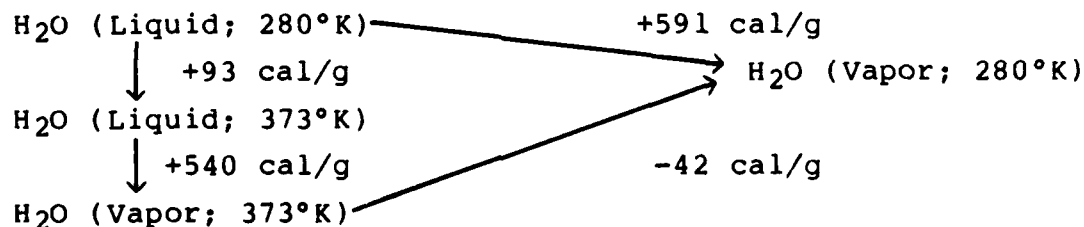
4. To condense 1 g water vapor into liquid at 280°K yields 590 cal = 2450 joule* (into ice at 250°K, 690 cal = 2860 joule) so that condensing 2 g H₂O/kg in a mass M_0 of Eq. (G.1) releases an energy

$$E_{cond} \sim 2 \times 2450 \times 10^3 \times M_0 = 4.5 \times 10^{19} \text{ joule} \quad (\text{G.5})$$

5. The latent (or other) heat released is transformed locally into kinetic energy of translation or rotation; the energies here are somewhat smaller. A velocity of 10 m/sec (20 knot) corresponds to a kinetic energy of 50 joule/kg or

*Because c_p (ice) = 0.5 cal/g °C
 c_p (water) = 1.0 cal/g °C
 c_p (vapor) = 0.45 cal/g °C

we have the following cycle:



$$E_{KE} \sim 50 M_O = 4.6 \times 10^{17} \text{ joule} \quad (G.6)$$

about 1 percent of E_{th} , E_{pv} , or E_{cond} .

6. Finally, the solar constant $S_O = 1400 \text{ W/m}^2$, so that an 8-hour equivalent irradiation of an area $d^2 = 10^6 \text{ km}^2$ provides an insolation

$$E_{sun}/\text{day} \sim S_O \times (8 \text{ hours}) \times d^2 = 4.0 \times 10^{19} \text{ joule} \quad (G.7)$$

Of course, only a fraction of this is absorbed by the air mass.

7. These numbers are presented for general orientation, to indicate how large both the mass and energy content of a meteorological air mass are, even compared with a major nuclear engagement. For the modeled burning of the city of Detroit shown in the figure on p. 3-5, one infers that a total mass of 5.6×10^6 tonnes of fuel burned, or (assuming the heating value listed on p. 1-3 of $1.86 \times 10^7 \text{ joule/kg} = 8000 \text{ BTU/lb}$) a heat of combustion of $10^{17} \text{ joule} = 24 \text{ Mt}$ equivalent. Explicitly, it is thus moderately difficult for a nuclear engagement to change the state of the atmosphere in a gross way, although this by no means eliminates the possibility of a higher-order perturbation such as Nuclear Winter.

APPENDIX H

ON THE 1982-1983 BORNEO (EAST KALIMANTAN) FIRES*

General Description (Provided by Scott A. Jackson, Georgia Pacific Corporation, Atlanta, Georgia)	H-3
Satellite Imagery from a Polar Orbiting Weather Satellite	H-5

*The drought which led to the 1982 Borneo fires is related to the 1982 El Nino event, which was a major and unusual environmental excursion of the "Southern Oscillation." For an overview, see Rasmusson and Hall (1983).

GEORGIA-PACIFIC'S INVOLVEMENT IN EAST KALIMANTAN

Georgia-Pacific, in a joint venture with some Indonesian companies, managed three timber concessions and operated two plywood mills in East Kalimantan, Indonesia until February of this year. All interests in the Indonesian Operations have been sold to the joint venture partners.

The three timber concessions were never owned by Georgia-Pacific or the joint venture partners. The Government of Indonesia maintained ownership of the land and timber. Rights to harvest timber were granted under the concession agreement to the joint venture. Terms of the concession agreement included restrictions on timber harvesting methods, road construction methods and requirements for reforestation of harvested areas.

TIMBER HARVESTING PRACTICES IN EAST KALIMANTAN

The tropical rain forest of East Kalimantan contains more than 300 different tree species. Only eight to ten of these species are of commercial value. Two species, Meranti and Kapur, make up 90% or more of the total harvested volume. Approximately 50 cubic meters of wood is removed per hectare. This represents about eight trees per hectare out of a total of 80 to 100. Total volume per hectare is in the range of 200 to 400 cubic meters. Trees of no commercial value remain standing.

AREA INVOLVED

Almost all of East Kalimantan was affected by prolonged drought and fire. The Indonesian Directorate-General of Forestry (the government agency which administers all forest land in Indonesia) can provide specific information on the area in question.

TIME AND DURATION OF THE FIRE

It is normal practice under slash and burn agriculture to burn during the dry season, July through September of each year. The dry season started out in June of 1982 with the usual amount of burning. Burning continued until January of 1983 when there was a brief two week period of rain. Burning resumed until May of 1983 when heavy rains doused the fire. The period of January 1983 to May 1983 was the worst period. During these months there was virtually no rain.

CHARACTERISTICS OF THE FIRE

Tropical forest adjusts for times of drought by shedding excess foliage. The normal constraint on tropical forest growth is the fight for available sunlight and not moisture or nutrients. Therefore, during this period of drought the amount of leaves on the forest floor was much heavier than normal. The layer of leaves usually rots very quickly but lack of moisture prevented this process from occurring. The fire burned the layer of leaves and other small vegetation. Fire did not reach the crowns of the trees. Most areas burned more than once. The first burn consumed the original leaf layer on the forest floor. The trees shed more foliage as the drought continued and built up another layer of

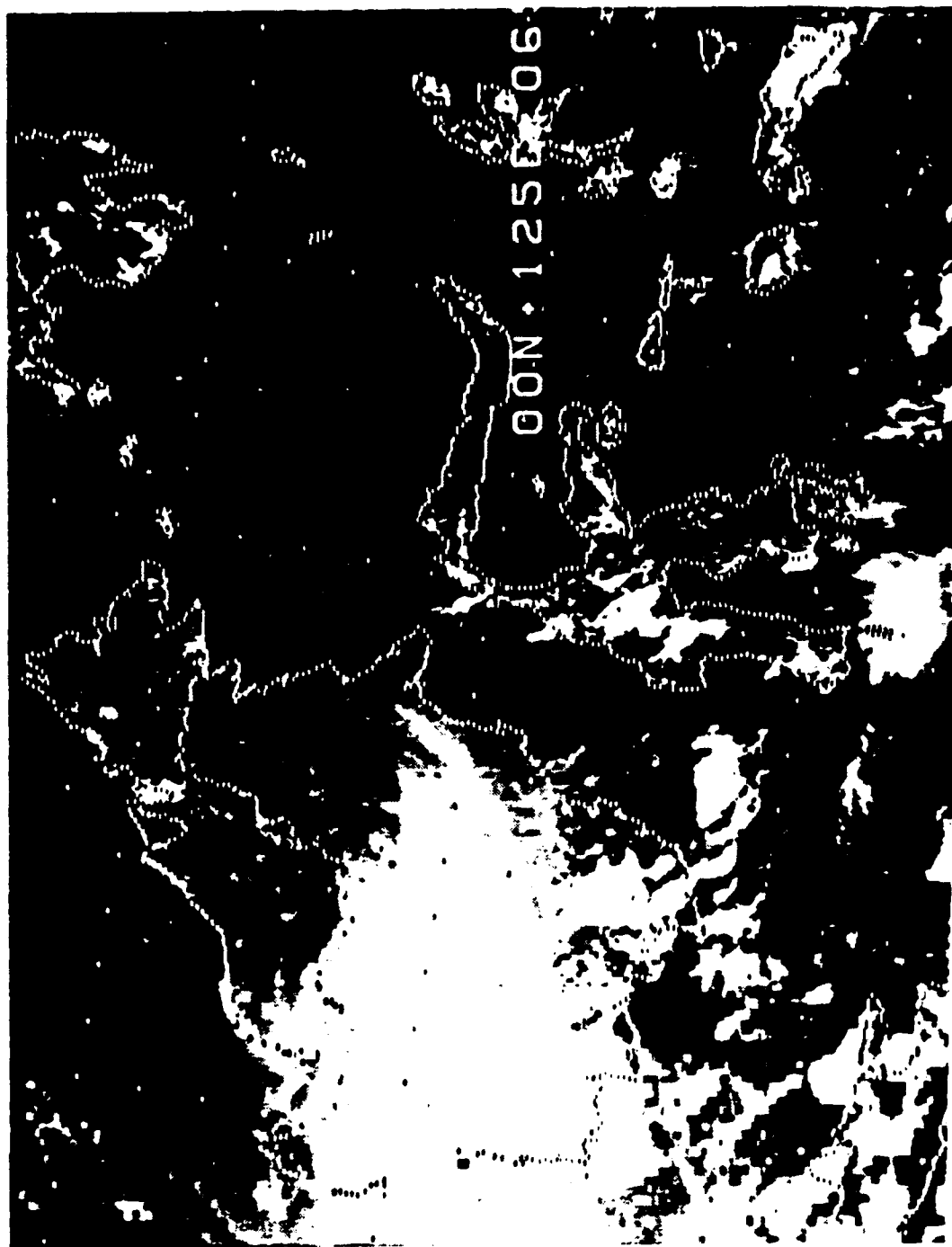
leaves. This second layer would burn again. The fire can be characterized as slow and "everywhere at once." Smoke from the fire was quite heavy to the point where maximum visibility was less than 500 feet for periods of weeks. The layer of smoke did not extend much beyond 8,000 feet in elevation.

TIMBER LOSS

In some areas the tree mortality was as much as 70%. Although many trees were killed by the fire, the majority of trees were killed by lack of moisture due to the drought.

HISTORICAL PERSPECTIVE

It is very rare to see virgin tropical rain forest burning. The last time there was a drought of this magnitude was about 60 years ago, as recalled by some of the older natives in the area. There was also a drought in East Kalimantan in 1974 which was not as severe.



1000 km

Forest Fires on Borneo. The Visible Channel on NOAA-7, 2 April 1983 shows the Smoke Plume in Gray (Top at 3 km) - Clouds are White.

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